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THE LAWS OF WINDS AND MOISTURE*

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LAWS CONCERNING WINDS

KINDS OF WINDS.

27. *There are three great kinds of winds: (1) planetary, (2) continental, and (3) cyclonic.*—The first are due chiefly to latitudinal differences in insolation; the second to differences in heating and cooling of land and water. Cyclonic winds are due in part to other causes, not well understood. Minor winds include mountain and valley breezes and winds associated with tides, land slides, earthquakes and explosions.[82]

DIRECTION OF WINDS.—*Effects of Temperature Differences.*

28. *Surface winds commonly blow from colder areas to neighboring warmer areas because warm areas usually have lower air pressure than nearby cooler areas, and winds blow from places of higher air pressure to places of lower air pressure, though at a small angle to the isobars where friction is slight.*—Great insolation along the heat equator gives

* Laws of Temperature were presented in the March, 1923, number of the ANNALS, pp. 15-40.

[82] Shaw, W. N.: Principia Atmospherica, Laws of Atmospheric Motion, *Mo. Weather Rev.*, Vol. 42, pp. 196-209, 1914.

rise to persistent winds (the planetary circulation). Other more local winds, due indirectly to differences in air temperatures, are land and sea breezes,[83] monsoons, and valley and mountain breezes. There are two exceptions to this general rule. If an area is excessively heated for a very short time, only the flow of air away from the heated area has time to take place.* Furthermore, with every mid-latitude cyclonic storm, part of the wind comes from warmer areas.

29. *A great system of winds (the planetary circulation) results from the combined influence of intense equatorial heating and of the earth's rapid rotation.*—Intense insolation produces low pressure along the thermal equator.[84] The deflective effects of the rotation of the earth produces low pressures in high latitudes (lowest about 60° instead of near the poles largely because of the chilling influence of the snow caps).[85] Between the equatorial and subpolar belts of lower pressure, a belt of relatively high pressure occurs near the margin of the tropics (averaging about 35° N. and 30° S., but shifting with the seasons). From the barometrically higher parts of this high pressure belt, winds blow toward the equator (the Trades) and toward the poles (the Westerlies in part). These higher centers of the Belt of Highs lie over the ocean because of the comparatively low temperature there, caused in part by the upwelling of cold waters.[86] The Horse Latitude Highs are maintained by the Anti-trades supplemented by the centrifugal force between the eastward blowing Westerlies and westward blowing Trades.†

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[83] Ward, R. De C., Land and Sea Breezes, *Mo. Weather Rev.*, Vol. 42, pp. 274-277, 1914.

* See Law 32, beyond.

[84] Blair, W. R., The Planetary System of Convection, *Mo. Weather Rev.*, Vol. 44, pp. 186-196, 1916.

[85] Shaw, W. N., loc. cit. pp. 208, 209.

[86] McEwen, G. F., Peculiarities of the Californian Climate, *Mo. Weather Rev.*, Vol. 42, pp. 14-23, 1914. Humphreys, however, believes that friction is the chief factor.

† The importance of the planetary circulation is so great that it seems worth while to supplement the foregoing simple statement with a fuller one which presents the causes in another way. This statement is based on one kindly contributed by C. F. Brooks.

The great heating of the air in the tropics results in a greater expansion there than in any other belt. The consequent raising of the layers of air especially over the heat equator causes a poleward overflow. Before reaching many degrees of latitude from the equator the deflective effects of the earth's rotation begins to affect this overflow until by the time latitude 30 or 35 is reached the poleward flow is largely arrested, by being converted into an eastward movement. The flow of air from the equatorial regions and its concentration at latitudes 30-35 N. and S.

30. *Appreciable local differences in the heating or cooling of the earth's surface often deflect general surface winds.* Cool areas such as snow-fields and lakes in summer often divert surface winds because such places commonly have a comparatively high air pressure, and hence tend to have outblowing winds.[87] Winds also sometimes change their direction during the day, blowing toward the area of greatest insolation.[88] Likewise lake and sea breezes often shift conspicuously, chiefly because of the deflective effects of the earth's rotation, but partly because of the hourly changes in the area of greatest heating.[89]

31. *Winds are deflected by the rotation of the earth, to the right in the northern hemisphere and to the left in the southern.* (Ferrel's Law.)[90] The deflective effect of the earth's rotation increases as the sine of the latitude from nil at the equator to a strong effect near the

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makes a low pressure belt in low latitudes and high pressure belts on either side, at the earth's surface. The low pressure belt is developed most strongly over the lands, where the expansion due to heating is greatest, and the high pressure belts are best developed over the oceans where the coolness allows a greater compactness of air than is possible over the hotter lands. In high latitudes the cooling over the polar ice-caps contracts the air and allows an inflow from the surrounding regions. In high latitudes, however, the defective effects of the earth's rotation are so great that such inflow can come from but limited distances. The result is the development, at the surface, of high pressures over the polar ice caps, and of broken rings of low pressure at latitudes 60 to 65. Here as in low latitudes the lowest pressures develop over the warmest portion for the latitude (here the ocean in winter, the land in summer), and the highest pressures over the coldest portion, the reverse. The surface winds induced by these belts of pressure tend to modify them by centrifugal action, which in the case of the westerly winds of middle latitudes intensifies the subpolar low pressure belts and the horse latitude high pressure belts, particularly over the oceans, where the slight friction favors strong winds. (The deflective effect of the earth's rotation, per se, cannot modify the wind velocities, and therefore cannot modify gradients. It does, however, prevent the winds from obliterating gradients rapidly by direct flow. Centrifugal action, however, on curved wind paths can increase the gradient of pressure, and thus increase the wind.) Middle and high latitude lands in winter and intermediate and low latitude lands in summer, acting by themselves in cooling or heating the air, produce on a smaller scale the changes and circulation characteristic of the planet as a whole, and being superimposed on these worldwide changes, greatly complicate the distribution of pressure and the resulting winds.

87 Henry, A. J., The Winds of the Lake Region, *Mo. Weather Rev.*, Vol. 35, pp. 516-520, 1907, and Davis, T. H., Direction of Local Winds as Affected by Contiguous Areas of Land and Water, Ibid, Vol. 34, pp. 410-413, 1906.

88 Pernter, J. M., Causes of Diurnal Changes in Wind, *Mo. Weather Rev.*, Vol. 42, p. 661, 1914.

89 Humphreys, W. J., in National Research Council, Introductory Meteorology, p. 106, 1918.

90 Ferrel, Wm., A Popular Treatise on the Winds, 1890.

poles.[91] As a result of this deflective effect the Trades are easterly instead of north or south winds, and the planetary winds of mid-latitudes are westerly, instead of north or south winds. Land and sea breezes "veer" notably in the northern hemisphere and "back" in the southern chiefly because of this deflective effect. The direction of the winds about Lows and Highs and in tropical cyclones also complies with Ferrel's Law.

Effects of Topography.

32. ***The prevailing wind direction is peculiar at many points, especially in rugged regions, because surface wind directions are influenced by topographic features.***—Mountain ranges and lesser elevations frequently divert winds, for winds tend to descend valleys and other slopes,[92] because gravity interferes with ascent but facilitates descent. For the same reason wherever slopes are ascended by general winds, valleys are often followed conspicuously.[93]

Seasonal Changes in Direction.

33. ***A seasonal change in average wind direction is common.*** Changes are produced in three ways: (1) By the seasonal migration of the wind belts, (2) by the development of typical monsoons, (3) by the frequent deflection of the planetary winds caused by high and low pressures produced by unequal heating and cooling of continent and ocean. Many subtropical areas are within the Trade Wind belt in summer and within the Westerly wind belt in winter. Other subtropical or warm temperate areas have land monsoons in winter and ocean monsoons in summer. Farther north, in the northern hemisphere, there is likewise a seasonal change in average wind direction due to changes in average barometric pressure. Continents commonly have high average pressures in winter and low average pressures in summer. Thus there is a strong tendency for barometric minima to develop over oceans in winter. Hence southerly or westerly winds predominate in winter on western coasts, and northwesterly winds on eastern coasts. For example, southwest winds predominate in winter in western Europe and in western North America, north of California, while northwest winds prevail in eastern North America and in eastern Asia.

[91] For table showing radius of curvature of deflection for different latitudes see Davis, W. M., Elementary Meteorology, p. 104, or Milham, W. I., Meteorology, p. 161.

[92] Day, P. C., Winds of the U. S., *Yearbook of the Dep't of Agriculture for* 1911, p. 340, and Henry, A. J., Climatology of the U. S., *Bull. Q., U. S. Weather Bureau*, pp. 67-75, 1906.

[93] Davis, W. M., Elementary Meteorology, p. 98, Figs. 29, 30; 1894.

Conversely, in summer low pressure over the drier parts of the continent commonly give rise to southerly winds on the eastern side of the continents, and northwesterly winds on the western side. For example, the average wind direction in summer for the eastern half of the United States, is from the southwest or south and that of eastern Asia from the southeast, while at the same time western Europe and western United States are having northwesterly winds.[94]

Changes with Altitude.

34. *Wind direction aloft is different from that nearer the surface usually being more to the right of the surface direction* (in the northern hemisphere). At higher and higher elevations up to a height of about 2,000 feet (610 m.) the wind makes a progressively greater angle with the line representing the steepest gradient, that is, they blow at a smaller angle with the isobars. This is because with decrease in friction the flow of air with a given gradient is more rapid, and therefore the deflection is greater, thus bringing the wind direction more nearly parallel to the isobars. At even higher elevations, where friction is only slightly less, wind direction continues to change, becoming progressively more nearly parallel with the isobars, which at high altitudes seldom depart more than 30° from an east-west direction. This change is because of the increase in centrifugal force which accompanies increased velocity, and occurs in spite of the fact that the decrease in the earth's rotational deflective effects, which accompanies the increase in wind velocity with altitude, tends to make the wind direction less nearly parallel to the isobars. The weakening of the pull of gravity permits the centrifugal tendency to overcome the tendency to turn to the right (northern hemisphere).[95]

Diurnal Changes.

35. *Surface winds at low altitudes often "veer" during the day and "back" at night. At higher altitudes the diurnal shifting is commonly in the opposite direction.*—A diurnal change of 12° in wind direction is common. This shifting is due largely to convectional inter-

[94] Hann, loc. cit., pp. 172-178, gives several tables showing average monthly wind directions for stations in Europe, Asia, and North America. He also states that continents resemble cyclones in summer and anticyclones in winter. Köppen's charts for normal wind directions on the ocean for July-August and Jan.-Feb. are reproduced in Moore's Descriptive Meteorology and in Humphreys, Physics of the Air. See also Ward R. De C., The Prevailing Winds of the U. S., *Annals Assoc. Am., Geographers*, Vol. 6, 1916, pp. 99-116 (abstracted in *Mo. Weather Rev.*, Vol. 47, pp. 575-576, 1919).

[95] See Shaw and others, Meteorol. Glossary, loc. cit., pp. 134-137, 171-173 and also Humphreys: Wind Velocity and Elevation, *Mo. Weather Rev.*, Vol. 44, pp. 14-17, 1916.

change between the wind at the earth surface and that at a moderate elevation. During the day, convection causes masses of air from above to descend to the surface. These layers tend to retain their somewhat different direction of general movement, mentioned in the preceding law. Hence at low altitudes there is a tendency to shift to the right in the northern hemisphere (" veer "). At night, when convection is much less intense or is lacking, the surface friction forces the wind to blow at a larger angle with the isobars and as this adjustment takes place the wind shifts counter-clockwise (" backs "). At higher altitudes, a few hundred feet above the surface in winter and 2,000 or 3,000 feet (610 or 914 meters) in summer,[96] the wind direction changes in the opposite way to that at low altitudes because at night less friction is induced by upward convection than by day, since there is comparatively little convection at night. Hence the air at higher levels can flow at a smaller angle with the isobars by night than it can by day. Along coasts there is often a marked progressive shifting in the land and sea breeze. Sometimes it reaches nearly 90°.[97] This shifting is produced chiefly by the deflective effects of the earth's rotation on the air which comes from a progressively greater distance from the shore line until the breezes finally die down.

WIND VELOCITY.—*Variations with Latitude and Altitude.*

36. *Average wind velocities increase with latitude to about 45° or 55° N. and S., except for the horse-latitude calm belt.*—This is because winds strengthen, on the average, with the steepening of the barometric gradient and the greatest average interzonal gradients are about 45°-55° N. and S. The correspondence between gradient and velocity is not constant, however, because of various influences, some of which are mentioned below. Normally in mid-latitudes, a ten-mile-an-hour (4.5 meter per sec.) surface wind is to be expected when isobars representing a barometric difference in pressure of one-tenth inch (3.4 mb.) are 170 miles (270 km.) apart, a 25-mile (11.2 meter per sec.) wind when such isobars are 70 miles (110 km.) apart, and a fifty-mile wind (22 m. p. s.) when 35 miles (56 km.) apart.[98] Above the surface 1500 feet (460 meters) or so the wind is little affected by surface conditions and hence the relation between gradient and velocity is much closer,

[96] Hellmann, *Mo. Weather Rev.*, Vol. 45, p. 454, 1917; Dunoyer and Reboul, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918. Taylor, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918.

[97] As at the Chicago Crib in July where the wind is normally from the east at 1 P. M. and shifts to nearly due south by 10 P. M., Davis, loc. cit., p. 135. See also Cox and Armington, The Weather and Climate of Chicago, p. 305, 1914.

[98] Walz, after G. Guilbert, in Weather Forecasting in the U. S., p. 140, 1916.

as is also the case at sea. Under such conditions the winds become almost gradient winds. The velocity of gradient winds is almost exactly doubled as the distance between isobars is halved. Where isobars of .3 inch (10 mb.) are about 900 miles (1450 km.) apart, the wind blows about 11 miles per hour (5 meters per sec.), and where about 100 miles (161 km.) apart, the velocity is about 100 miles per hour (45 m. per sec.). The gradient velocity increases, however, with latitude, about 20 per cent between latitudes 40 and 52, and decreases with increasing temperature, about 10 per cent between 32° F. and 104° F. (0° C. and 40° C.).[99] The increase in average velocity with latitude (to about 45 or 55 N. and S.) is also associated with the average increase in storminess to about those latitudes. Furthermore, wind velocities are on the average slight near the equator partly because the deflective effect of the earth's rotation is so small there that the air flows rapidly into an area of low pressure and fills it promptly and then dies away instead of circling round and round as it does in higher latitudes. The decrease in average velocity in polar regions is not due to the total lack of strong winds, for gales, usually of the drainage or the monsoon type but sometimes foehns, often occur locally in polar regions, especially near the edges of glaciers. However, calms are frequent, so the average wind velocity for polar regions is low.[100]

37. *Wind velocity normally increases with altitude, rapidly over an area of much surface friction and less rapidly over an area of little friction,* such as the sea. There is commonly a rapid increase in velocity from the surface up to the height of the taller local objects interfering with air movement (trees, hills, etc.).[101] Above that level the increase is at a much lower rate; between 2000 feet and 3300 feet (600 and 1000 meters) there may be no considerable increase. Above an elevation of a mile or so (2 km.), there is an average increase of between one and two miles per hour (.5-.9 m. per sec.) for each rise of 1000 feet (300 m.), up to an elevation of three to five miles (5-8 km.), an increase in velocity sufficient to compensate for the decrease in density, so that each 1000-foot layer carries the same mass of air past a given

[99] Computed from Shaw, Meteorol. Glossary, pp. 172-173.

[100] Ward, Climate, p. 174, Wilkes Land in the Antarctic is an exception (Ibid, p. 176). There cyclonic storms are severe. Also see Simpson, G. E., The Meteorology of the Antarctic, *Mo. Weather Rev.*, Vol. 49, pp. 305-306, 1921.

[101] The greater velocity commonly recorded at U. S. Weather Bureau Stations in large cities than in small places is because the city aneometers are located on relatively tall buildings. Near the ground the average velocity of the wind is proportional to the 4th or 5th roots of the heights, according to Hellmann, *Mo. Weather Rev.*, Vol. 47, p. 574, 1919. In other words, according to Chapman, (Ibid, p. 572) it is a lineal function of the logarithm of the height.

line per hour. (Clayton's Law, often known as Egnell's Law). The velocity increases to an altitude of about five miles (8 km.), where it often reaches more than 100 miles per hour (45 m. per sec.).[102] Beyond the five-mile level (8 km.), Clayton's Law does not hold, and the velocity falls.

38. *Surface winds average stronger over smooth surfaces than over rough, in similar latitudes* because surface friction reduces the velocity which can occur with a given barometric gradient. Hence winds are normally stronger on water than on land, stronger on plains than over rugged areas, and stronger over grass-covered or barren areas than over forests. A mantle of snow or ice also tends to increase wind velocity by lessening friction. The average velocity of surface winds on the sea is estimated to be twice that of winds on land.[103] Hence along the coasts the average velocity is notably higher than it is a short distance inland. For example, the wind velocity is often only half as great on the east coast as on the west coast of the British Isles, with a west wind and equal barometric gradients.[104]

Effects of Insolation and Humidity.

39. *Winds are often especially strong at the surface by day in places of great insolation.*—This is because convection is strong and hence rapidly moving air from above replaces the warmed air as it rises, in fact causes it to rise. Where much air is quickly warmed, large amounts of rapidly moving air usually descend. Even if they do not descend to the surface, they increase the friction between the surface layers and the faster moving upper layers, which tend to drag the lower air along.[105] The extent of this knitting by day has been discovered by aviators who find that currents induced by local convection are often noticeable at heights of 2000 feet (600 m.) and sometimes 10,000 feet (3,050 m.) or more above the surface on clear days.[106] Hence where a heavy mantle

[102] Humphreys, W. J., Wind Velocity and Elevation, *Mo. Weather Rev.*, Vol. 44, pp. 14-17. However, Maurain, C., Ibid, Vol. 47, p. 809, 1919 gives much lower velocities. He reports the maximum velocity experienced by many balloons to be 15.6 meters per sec., (35 miles per hour) and at 11,000 meters 67 miles. Above that height a decrease occurs to about 18 miles per hour (8m. per sec.) at 19,000 m. (12 miles). Velocities in excess of 100 miles an hour (45 m. per sec.) are rare, according to these French balloon data, but one balloon travelled at the rate of 123 miles an hour (55 m. per sec.). A balloon over England travelled 180 miles per hour (80 m. per sec.) at 26,000 feet (7925 m.) on Jan. 19, 1920 Ibid, Vol. 48, p. 41, 1920.

[103] Meteorol. Glossary, loc. cit., p. 122.

[104] Ibid., p. 123.

[105] Pernter, loc. cit., p. 662.

[106] Brooks, C. F., Effects of Winds and Other Weather Conditions on the Flight of Airplanes, *Mo. Weather Rev.*, Vol. 47, pp. 523-525, 1919.

of clouds retards insolation, as is often the case in humid climates, the surface wind velocity on a hot day is often much less than on a clear day with its usually greater convection. Often narrow, deep valleys may be nearly calm in spite of intense insolation because the wind, if at right angles to the valleys, may not descend to the floor of the valley before it commences to ascend the other side. An example is Death Valley, California.

40. *Winds associated with rapid convection are strongest in the season and at the time of day when convection is greatest,* which usually is shortly after the time of greatest insolation. Although insolation is greatest and the vertical temperature gradient is steeper just before noon than at noon, convection commonly intensifies for some time after noon, and after the summer solstice. Insolation averages greater just before noon than at noon because of less average cloudiness then; convection is greater shortly after noon and after the summer solstice than when the sun is most nearly vertical because of the lag in surface temperatures (Law 14). Thunder-storms with their associated squall winds occur on the land chiefly in early summer in mid-latitudes and at corresponding seasons in low latitudes. Dust whirl-winds also are most frequent then and near noon. Tornadoes are most numerous in May and June in the northern hemisphere. On the other hand, upon the ocean, in high latitudes especially, the vertical temperature gradient is greatest in winter, because then the surface air is kept relatively warm by the water. Hence high-latitude ocean thunder-storms are most frequent in winter.[107]

41. *With a given barometric gradient, wind velocity tends to increase slightly with absolute humidity,* because water vapor is less viscous and lighter than dry air. (Molecular weight of air is about 29, while that of water is only 18.) The wider average spacing of isobars in the warmer latitudes and in summer is in part an indirect result of this greater amount of water vapor.[108]

Effects of Direction.

42. *Non-planetary winds blowing with the planetary circulation are stronger than similar winds blowing in other directions* because the planetary circulation augments their velocity if they are blowing with it, or checks their velocity if they are blowing against it. This law largely accounts for the "dangerous side" (poleward, right) of tropical cyclones; for the greater velocities on the equator-ward (right) side of extra-tropical cyclones and on the poleward side of anti-cyclones; for the greater influence of sea and lake breezes on the eastern shores

[107] Humphreys, Physics of the Air, p. 324.

[108] Davis, loc. cit., p. 153.

of water bodies in the belt of Westerlies and on the western shores in the Trades; and also for stronger monsoons on one side of some land areas than on other sides quite similar in other respects.

43. *Exceptionally cold winds are often more powerful than relatively warm winds* because such cold winds commonly have a greater velocity and density. The greater velocity is partly caused by the recent descent from somewhat higher altitudes, of which their greater than average downward component is evidence.[109] It is also associated with the steep pressure gradient caused by the exceptionally cold and therefore dense air of the northwesterly winds in contrast to the warm southerly winds usually occurring immediately to the east (in the Northern Hemisphere). Their greater density is related to their low temperature. Their density enables them to push harder than less dense winds. In the northern hemisphere, northwest winds average the coldest. They also average the strongest, for the above mentioned reasons and because they are aided more by the prevailing westerlies than are the winds from most directions.

Seasonal and Diurnal Variation.

44. *Wind velocities average greater in winter than in summer in mid-latitudes.*—The lessened average barometric gradient of summer which largely produces the lesser summer velocity is related to: (1) lessened storminess in summer (most widespread high winds in mid-latitudes are associated with intense Lows); (2) the greater absolute humidity of summer permits a freer wind movement and thus tends to facilitate an equalization of barometric differences; (3) the fact that the isotherms are farther apart in summer than in winter results in the isobars usually being far apart also; (4) the barometric gradients are also affected by the temperature gradients, which often are steeper in winter than during most of the summer. Another factor tending to reduce the velocity of the wind in summer is the greater friction resulting from vegetation and from local contrasts in surface heating with their resulting convectional disturbances. Gales are commonly much more frequent in winter than in summer. For example, on the British coasts, gales are more than six times as likely to occur on any day in the six months October to March, as on a day in the three months June to August.[110]

[109] See H. H. Kimball, Northwest and Southwest Winds Compared, *Mo. Weather Rev.*, Vol. 48, p. 147, 1920.

[110] Meteorol. Glossary, p. 127. In some other areas, gales are most numerous in spring. For example, in South Dakota, though there are fewer gales in Dec. and Jan. than in summer, there are more than twice as many in April and May as in July and August. (Visher, S. S., Climate of S. Dak. p. 51, *Bull. 8, S. Dak. Geol. Surv.* 1918). In hurricane regions, on the other hand, gales usually are most

45. *The surface winds on the land commonly increase in velocity during the day until early in the afternoon, except at high altitudes on mountain peaks.* The increase in velocity accompanies the increase in convection.[111] It is due to an interchange of surface air and the faster moving higher air. The diurnal increase is greatest when the sky is clear. On cloudy days the maximum surface wind velocity is, on the average, only about half what it is when the sky is clear,[112] because on cloudy days convection is less than on clear days. At many places the average wind velocity is twice as great in the mid-afternoon as it is in the early morning. The diurnal variation in wind velocity almost disappears over the ocean with its nearly constant temperatures, and is less on the land in winter than in summer, and less on cloudy than on clear days, and less in the cooler regions than in warmer, because of the greater convection in summer and on clear days and in low latitudes. At high altitudes some distance above the surface, on the other hand, winds are stronger by night than by day chiefly because fewer convection currents reach a high level at night and hence there is less interference at night with the regular winds.[113] As an example: The average velocity on Pike's Peak is greatest from 2-4 A. M. (23.2 mi. per hour; 10 m. per sec.), and is least just before noon (17.5 mi. per hour; 8 m. per sec.). For the lowlands of the eastern United States, the hour of maximum wind velocity averages 2 P. M. and of minimum velocity 4 A. M., and the difference between minimum and maximum velocity averages two miles per hour (.9 m. per sec.) in winter and five miles per hour (2.2 m. per sec.) in summer.[114] At Kew, England, the diurnal variation averages six miles per hour (2.7 m. per sec.) in July and 2½ miles per hour (1.1 m. per sec.) in winter.[115]

frequent in autumn. (Visher, S. S., Tropical Cyclones of Australia, and the South Pacific and Indian Oceans and in the North Pacific, *Mo. Weather Rev.*, Vol. 50, pp. 288-297, 583-589, 1922).

111 Pernter, loc. cit., Taylor: Phenomena Connected with Turbulence in the Lower Atmosphere, *Mo. Weather Rev.*, Vol. 46, p. 211, 1918.

112 Russell, T., Meteorology, p, 106, 1895.

113 Hellmann, (*Mo. Weather Rev.*, Vol. 43, p. 58, 1915) ascribes this increase to the influence of the thermal wave caused by the earth's rotation. See Humphreys in Nat. Research Council, Introductory Meteorology, pp. 106-107, for additional, though probably very minor influences.

114 Waldo, F., Hourly Wind Velocities, *Am. Meteorol. Journ.*, Vol. 12, pp. 75-89, 145-151, 1895.

115 Shaw, Meteorol. Glossary, p. 86. The great diurnal increase in wind velocity at Hongkong is clearly shown on Plate 13 of Claxton, T. F., The Climate of Hongkong Royal Obs., 1916. The maximum normally is between 1 and 2 P. M. when the velocity averages one-third (4 miles per hour) more than at the minimum which occurs at 8 P. M. during 5 months, at 6 A. M. during 4 months and at 11, 2 and 7 A. M. on the others.

STEADINESS OF WINDS.—*Variations in Latitude and Altitude.*

46. ***In general there is a lessening of the persistence of winds with increased latitude accompanying the intensification of temperature variability,**** because winds vary in persistence with changes in the permanence of the conditions or conditional complexes that produce them. The Trades are notably persistent because of the steady heating along the thermal equator. Monsoons are less reliable than the Trades because of the greater variation in the heating of continental areas near the borders of the tropics than along the thermal equator. Lake and sea breezes are strongest and most persistent when there is greatest temperature contrast between land and water, as on clear days in hot seasons. Sea breezes are exceptionally prominent on west coasts in the Trade Wind belt for there not only is the land heated greatly by day but the surface ocean water is exceptionally cool by day as compared with the land, largely because of the upwelling of cold abysmal waters induced by the drift to the westward (contributory causes of the coolness are mentioned in Law 5). In general the sea breeze is better developed than the land breeze because the land is warmer than the sea throughout the year in low latitudes and in summer, the season of sea breezes, in higher latitudes.[116]

47. *Winds tend to increase in steadiness with altitude in the free air and on windward slopes, up to considerable heights,* because friction is less and disturbances are fewer.† The change with altitude is especially marked at night. In large parts of the world fitful breezes are the rule at night at the surface on lowlands, while at moderate elevations the wind is blowing steadily. (See next law.) The same condition often obtains on lowlands along coasts, before the sea breeze and land breeze make themselves felt at the surface.[117]

Variation with Diurnal Range of Temperature.

48. *Calm nights are common wherever the surface becomes much colder at night than it is by day,* and hence are characteristic of trade wind deserts and other dry parts of the land. Calm nights are abnormal on the ocean, except in the belts of calms, because of its nearly uniform surface temperatures.[118] Winds commonly die down at the surface of

* See Law 25, above.

[116] Hann, loc. cit., p. 160.

† See Laws 37, 38, 45, 48, 49, 50, for some effects of increased altitude on winds

[117] Davis, W. M., Elementary Meteorology, p. 136, 1894.

[118] Humphreys points out (Physics of the Air) (p. 324) that because of the greater nocturnal cooling of the air than of the surface water, the temperature gradient over the ocean is most favorable to convection shortly before sunrise. Hence convection currents and thunderstorms are most numerous then. Surface wind velocity must also be greatest then, wherever the influence here discussed is dominant.

the land at nightfall because this surface is a comparatively good radiator and since it has a lower specific heat than air, it is soon cooler than the over-lying air. After the surface air is cooled by conduction and moderate radiation to the cooler earth, upward convection largely ceases because the colder, heavier air is at the bottom of the atmosphere. Friction tends greatly to retard the movement of this lower, heavier air. The wind tends to slip over the surface layers, and if it does slip over them a surface calm is induced. The completeness of the surface nocturnal calm depends on the amount of nocturnal convection, the amount of friction, and the character of the wind. In dry regions, loss of heat by radiation is exceptionally rapid, and hence convection largely ceases soon after sunset. There is more friction over land than over water, and more in forested and rugged parts of the land than in grass covered or level areas. Winds with a notable downward component tend to prevent the development of a surface calm, whereas winds with an upward component favor its development. The Trades are of the latter sort,[119] as are the winds blowing into a Low from the equatorward side.[120] Those from a High, and on the poleward side of a Low have a distinct downward component. However, calms are frequent near the center of anticyclones,[121] where there is little or no barometric gradient to induce winds. In respect to latitude, the amount of nocturnal surface calm decreases, among places otherwise similar, with increase in latitude up to the poleward side of the great storm belts, roughly to latitude 55° N. and 45° S. This is because to the poleward of this belt, diurnal range is less, and cloudiness and equatorward blowing winds more frequent.

Sudden Changes (*Gustiness and Puffiness*).

49. *All winds vary in velocity and direction from minute to minute.* —Variation in direction, here called "gustiness" is considered in the following law. Variation in velocity, here called "puffiness," is caused largely by the convectional and frictional forces which produce variations in direction. One additional cause for continual change in velocity is the variation in pressure due to the passage of waves through the air, for example those oscillations associated with the constant shift, produced by the earth's rotation, in the longitude of greatest insolation. Frequent slight variations in air pressure are produced over the sea

[119] Abbe, C.: The Mechanics of the Earth's Atmosphere, a Collection of Translations, *Smithsonian Miscellaneous Collections*, 843, 1893. (Paper by Prof. Oberbeck, p. 186.)

[120] Blair, W. R., Planetary System of Convection, *Mo. Weather Rev.*, Vol. 44, p. 192, 1916.

[121] Shaw, Meteorol. Glossary, p. 31.

by the water waves and troughs. Tidal waves have some effect on air pressure even over the land. The fall of rain, the roll of thunder, and similar disturbances likewise produce slight variations in pressure. The elasticity of the air and its inertia are fundamentally important in connection with "puffiness." Variations in "puffiness," although always present, increase in amplitude, as expressed in miles per hour, with velocity of the surface wind. Often there is a variation of 10 or 20 miles an hour (4½ to 9 meters per sec.), in a few minutes during a high wind. If expressed in per cents, the momentary increases are greatest when a breeze prevails, for then the velocity may double or triple within a few minutes. "Puffiness" is especially conspicuous over a storm-tossed sea, and it also appears to increase with latitude up to the storm belt. The winds about a well-marked Low are particularly "puffy."

50. *Momentary change of direction or gustiness increases on the average with increased surface friction, with approach to the desert, the equator and the bottom of the atmosphere, and in general with increase in convection and in local contrasts in heating.*—The decrease in gustiness with latitude is due to the fact that convection decreases on the average with increase in latitude. The increase with aridity accompanies a general intensification of convection. Objects which produce friction cause some air to rise and later to fall, in order to pass over the object or over the air which has been piled up as a result of friction.[122] Gustiness decreases with height above the surface because most vertical currents induced by local convection or friction only affect the lower few hundred feet of air, and relatively few affect as much as the lower 2500 feet (760 m.).[123] (Vertical local convectional currents are felt twice as high in summer as in winter in some regions).[124] Local contrast in heating is produced by contrasting types of soil or vegetation, the presence of bare areas, of streams, of small lakes or marshes, and of significant differences in slope or relief. Such differences often produce gustiness because air often rises above the warmer areas and descends over the cooler. Cumulus clouds are striking evidences of

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[122] Convection is also caused by overriding of one layer of air by another. Easterly winds especially are lighter than westerly winds and are often overridden. This would tend to produce convection. (Shaw, W. N., *Mo. Weather Rev.*, Vol. 42, p. 198, 1914; and see also Brooks, Kimball and Humphreys, Ibid., Vol. 48, pp. 100, 101, 147; 1920.

[123] "Gustiness falls off rapidly in the first 500 feet of ascent, and thereafter it is irregular." Dines, W. H., Meteorol. Glossary, p. 142.

[124] Brooks, C. F., Winds and the Flight of Airplanes, *Mo. Weather Rev.*, Vol. 47, pp. 523-525, 1919.

such unequal heating.[125] Wherever and whenever local convection is least, gustiness due to local convection is least. Therefore this type of "bumpiness" is less in the relatively calm, cloudless weather of an on-coming High than in an on-coming Low with its patches of clouds, and its stronger winds.[126] Because of the importance of local convection in producing gustiness, the latter is far less noticeable over the sea than over land,[127] at night than by day, in winter than in summer, and less intense over a fog or low cloud than at corresponding altitudes where such barriers to insolation and convection are not present. The lessened gustiness over the sea and on the land in winter is due to the comparatively slight friction. Gustiness increases with aridity only where surface conditions are similar, which seldom is the condition. In arid regions there usually are few trees, fields, roads and buildings. Hence there is less contrast and less friction. Thus, instead of increasing with aridity, gustiness often decreases. Gustiness was not considered as an aspect of climate until surveyors, astronomers and aviators revealed considerable geographic permanence of differences in "visibility" and in "bumpiness." Surveyors find that the visibility of distant objects usually decreases from morning to mid-afternoon and then increases; that the "seeing" is better on a cloudy day than on a clear or partly clear day; and that on clear days "seeing" is better in cool climates than in warm. These variations in visibility are apparently related to local convection, the great cause of gustiness. Astronomers find the "seeing" poorest on windy nights and best on calm nights. The fact that nocturnal "seeing" is especially favorable in deserts is probably related not so much to less humidity, as to the lack of nocturnal convection. The excellent vision at night at Mandeville, Jamaica, where the annual rainfall normally is 87 inches (2210 mm.), but where, for special reasons, the nocturnal convection is slight, supports this view.[128]

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125 Another excellent indicator of convection and of turbulence due to friction is smoke from a smokestack. See Etkes and Brooks, *Mo. Weather Rev.*, Vol. 46, pp. 459-460, 1918.

126 Shaw, Meteorol. Glossary, pp. 21-23.

127 Taylor, loc. cit.

128 Pickering, W. H., *Mo. Weather Rev.*, Vol. 47, p. 574, 1919; and Vol. 48, p. 511, 1920.

LAWS CONCERNING ATMOSPHERIC MOISTURE

Sources of Moisture.

51. *Atmospheric moisture is derived by evaporation from all moist surfaces, chief of which is the ocean,* as the ocean covers three-fourths of the globe and more than four-fifths of its warmer half. Evaporation from soil, vegetation, animals and water on the land is the immediate source of much vapor. It should be borne in mind however, that a lake, even a large lake, is no more an ultimate source of water vapor than is ground moistened by a shower; both are temporary resting places of water en route to the sea. Nevertheless, much rainfall on the land is derived from moisture recently evaporated from such resting places. The small amount of evaporation taking place at low temperatures during the winter, when there is often much snow or other moisture on the ground, is one cause for the lesser precipitation in the cold season than in the warm in many inland places. When spring comes with its higher temperatures, accumulated moisture of the winter is soon largely evaporated and often partly reprecipitated, giving rise to spring showers. Some of it remains in the air, however, until the autumnal cooling.

Rate of Evaporation.

52. *The potential rate of evaporation at any point normally increases with the temperature and hence usually is greatest at the warmest time of the day and year.* At night condensation often takes place instead of evaporation. This variation occurs because the capacity of space to hold moisture increases sharply with the temperature. Twenty times as much moisture can be contained in a given space at 100° F. (38° C.) as at 15° F. (—9° C.).[129] The capacity is approximately doubled or halved with each change of 18° F. (10° C.). The local rate of evaporation is affected also by the wind velocity and, as there commonly is also a diurnal intensification of wind velocity corresponding with the diurnal rise of temperature,[130] the wind regime helps explain the diurnal change in evaporation. The wind is significant as a factor affecting the rate of evaporation because it carries away the saturated or partly saturated air. When other conditions

[129] Tables of capacity in vapor pressure and in quantity of water vapor per cu. ft. at different temperatures are given by Milham, Meteorology, p. 195, and in texts on physics. A full table showing vapor pressure for relative humidities at different temperatures is given in *Smithsonian Meteorol. Tables*, pp. 183-185 and pp. 192-193, 1918.

[130] The close similarity of the diurnal curves of temperature and wind velocity is strikingly illustrated at Chicago. See Cox and Armington, Weather and Climate of Chicago, p. 314, 1914.

are uniform, the rate of evaporation is roughly proportional to the square root of the wind velocity.[131] The influence of the higher average velocity of wind in winter, however, is usually counteracted by the lower temperatures.

The rate of evaporation depends also upon the humidity of the air in contact with a moist surface and the temperature of that surface. If the surrounding air contains much less moisture than it can hold at its temperature, evaporation will be relatively rapid; if it is nearly saturated, evaporation will be relatively slow. If the moist surface is warm, evaporation is more rapid than if it is cold. The more rapid evaporation on clear days than on cloudy days in mid-latitudes is due chiefly to the fact that air is commonly drier on clear days than on cloudy days, even though it is sometimes cooler. The greater insolation in clear weather is significant because it tends to maintain the surface temperature, and thus allows evaporation to continue at a faster rate than the dry air alone would permit. Clear days in mid-latitudes usually are associated with anticyclones in which the air is descending and being warmed dynamically.

53. *The rate of evaporation diminishes on the average at progressively higher latitudes and altitudes and also with approach to marine conditions.* The change with latitude is associated with a like change in temperature. The Trades are drying winds except where ascending because they blow into progressively warmer latitudes. Decrease in the rate of evaporation with approach to marine conditions is influenced by increased relative humidity, and in all but cold places, also by lessened average temperatures. Within the tropics there is an average annual evaporaton of 30 inches (760 mm.) and in the polar regions less than 10 inches (250 mm.). In general, evaporation exceeds precipitation in the lower latitudes while precipitation exceeds evaporation in the higher latitudes.

The general decrease in evaporation with increase in altitude is the result of lessened temperatures and this decrease takes place in spite of the influences of decreased air pressure, lower absolute humidity, and stronger winds, all of which tend to increase the rate of evaporation. Hence, whenever temperatures at high altitudes are equal to those at low altitudes the rate of evaporation tends to increase with altitude. Furthermore the low absolute humidity characteristic of high altitudes strikingly affects the rate of evaporation whenever temperatures are suddenly raised. When cold air, saturated perhaps but containing only a little moisture, is warmed, it becomes relatively dry, and thus evaporation is facilitated. Marked surface heating by insolation, which

[131] Hann, Handbook of Climatology, Vol. 1, translated by Ward, p. 44, 1903.

is fairly frequent at high altitudes and occasional in high latitudes, thus often results in abnormally low relative humidities and also in rapid evaporation. The influence of decreased pressure upon evaporation where temperatures are high is illustrated by changes in the boiling temperature of water (a form of rapid evaporation). There is a lowering of 1° F. for each decrease in pressure of about .6 in. (1° C. for 37 mb.). Each rise of 550 ft. (178 m.) produces such a change in average pressure. Water boils, at all levels, at a lower temperature, sometimes as much as 3° F. (1.7° C.) lower, in a Low than in a High.[132]

DISTRIBUTION OF MOISTURE.

54. *The windward sides of continents and of mountain ranges receive much more moisture, and hence more precipitation, than do the leeward sides* because atmospheric moisture is transferred chiefly by the wind. Diffusion is so slow a process that calms of sufficient duration to make diffusion significant are rare. Streams are the only other agent distributing much moisture. Rivers such as the Volga and Nile which carry large volumes of water into arid regions where it evaporates doubtless have some influence on the amount of atmospheric moisture in parts of their basins. The influence of winds on this distribution of moisture is illustrated in many places. For example, in the Hawaiian Islands an average of over 476 inches (12.1 m.) of rain falls annually on Mt. Waialeale, alt. 5075 ft. (1550 m.) on Kauai, while only 16 inches (406 mm.) falls on the leeward slope only 11 miles (18 km.) away. On another island (Maui) two stations only 7½ miles (12 km.) apart receive an average of 369 inches and 18 inches (9373 mm. and 457 mm.) respectively.[133] In the belt of Westerlies the condition near Seattle, Washington is noteworthy. Fifty miles west of Seattle, on the windward slope of the Olympic Mountains, the average precipitation is more than 120 inches (3500 mm.). At Seattle it is only 42 inches (1070 mm.) and an average as low as 18 inches (457 mm.) of rainfall occurs on some of the nearby islands in Puget Sound. Thirty miles east of Seattle, on the western slopes of the Cascades, more than 80 inches (2030 mm.) falls. A hundred miles east of Seattle, just east of the Cascades, the average precipitation is less than 10 inches (250 mm.).[134]

55. *The amount of atmospheric moisture* (*absolute humidity*) *nor-*

[132] Shaw, Meteorological Glossary, p. 300.

[133] Summary of Climatological Data for the Hawaiian Section, 1922 and *Mo. Weather Rev.*, Vol. 47, pp. 303-305, 1919.

[134] Chart of Average Annual Precipitation in the U. S., Atlas of American Agriculture, 1917. Reprinted in *Mo. Weather Rev.*, Vol. 45, Plate 76, 1917.

mally varies inversely with latitude and altitude, and as a rule, directly with distance from the sea,[135] because absolute humidity increases with the hastened evaporation which is induced by higher temperatures, and because warm air (space) can contain more moisture than cold. Water vapor makes up an average of 2.63% of the surface air at the equator; .92% at latitude 50 N. and .22% at latitude 70 N. The average for the earth is 1.2%.[136] Sometimes water vapor makes up as much as 5% of the weight of the air present over water bodies in warm areas.[137] This is equivalent to a vapor pressure of more than 1½ inches (38 mm.) of mercury. The atmosphere of the warmer half of the globe contains fully four-fifths of the total atmospheric moisture. The average decrease with latitude is illustrated in North Dakota, Nebraska, and Oklahoma, all of which are inland states in the same longitude and with similar amounts of rainfall. The average of the 7 A. M. and 7 P. M. vapor pressures for January, April, July and October is .20 in. (5 mm.) for North Dakota; .25 in. (6.3 mm.) for Nebraska; and .35 in. (9 mm.) for Oklahoma.[138] Decrease in absolute humidity with latitude is also illustrated by the statement that the air over Europe contains on the average enough moisture to yield about an inch (25 mm.) of water if it were all condensed, while condensation of all the atmospheric moisture over the eastern half of the United States would yield nearly 2 inches (50 mm.).[139]

The poleward decrease in vapor pressure is however not at a uniform rate. It varies with the effective distance from water bodies, with average temperatures, and with altitude.[140] In the storm belts, it is probably less than the expected normal for that latitude because the increased upward convection and precipitation in storms tend to lessen the absolute humidity.

Vapor pressure usually decreases inland rather rapidly. It often is approximately twice as great along the coast as in the drier portions of the continental interior in the same latitudes. This decrease is due to the fact that the moisture evaporated from the ocean and precipitated inland is not replaced by a like amount evaporated from the land.

The average decrease in water vapor with increase in altitude is

135 Day, P. C., Relative Humidities and Vapor Pressures over the United States, *Mo. Weather Rev., Supplement*, No. 6, pp. 5-61 and 24 charts, 1917.

136 Hann, Lehrbuch der Meteorologie, 3rd ed., p. 5, 1915.

137 Day, loc. cit., p. 6.

138 Calculated from data given by Day, *loc. cit.*

139 Day, *loc. cit.*

140 See also Table of Monthly Mean Water Vapor Pressures for Eastern, Central and Central Plateau States for four different latitudes given in *Mo. Weather Rev.*, Vol. 47, p. 772, 1919.

sharp. One-half the atmospheric moisture is within a mile (1.6 km.) of sealevel and at six miles (10 km.) the air contains only 1/120 as much as at sealevel.[141] This diminution is chiefly due to the decrease in temperature and hence in capacity, but in part to the fact that the atmosphere is supplied with moisture from below. Indeed all primary evaporation takes place at the bottom of the air.

56. *The absolute humidity is greater by day than at night, greater in summer than in winter and greater during wet periods than during dry periods.* The increase by day and in summer is related to the higher temperatures prevailing. The increased vapor pressure which commonly accompanies wet periods is caused chiefly by the larger supply of moisture from the sea brought inland by the winds. However, the larger amount of surface water and ground water available for evaporation, and actually evaporated, also plays a part.

The average diurnal increase of absolute humidity for the United States amounts to about 15%.[142] The increase is greater in summer than in winter especially if the actual increase and not the percentage of increase is considered. This is because a diurnal range of 30° F. (17° C.), for example, produces a greater change in the amount of moisture held if between 50° F. and 80° F. (10° C. and 27° C.) than if between 0° F. and 30° F. (—18° C. and —1° C.). Furthermore, nocturnal precipitation and dew and frost often greatly reduce the atmospheric moisture at night. In England, a country with high average humidity, the mean diurnal range is about 6%, varying from 5% in December and January to 8% in June and September. Among the months, there is nearly twice as much moisture in the air in July and August as in January and February.[143]

On the average, the vapor pressure is least about sunrise and greatest near mid-day. On the land the maximum comes shortly before noon in all warm places. On the other hand, it comes in the early afternoon in cool places such as the sea, and the land in winter. The normal relationship between absolute humidity and temperature, however, is often interfered with by convection. Hence wherever convection is intense, the absolute humidity at the surface of the earth usually is less shortly after mid-day than at any other time, because the warm moist air is then more easily displaced by drier air brought down by convection. In dry regions when convection is strong, there is often

[141] Humphreys, Physics of the Air, p. 69, 1920.

[142] Computed from Day, *loc. cit.*

[143] Meteorol. Glossary, *loc. cit.*, pp. 290-292. The monthly and diurnal variations in humidity are clearly presented for Hongkong, in Claxton, The Climate of Hongkong, 1916.

a decided decrease in vapor pressure as the hour of maximum temperature and convection approaches, because there is not enough evaporation to replace the moisture carried aloft by intense upward convection. Places, which because of nocturnal "inversion of temperature" have calm nights, may occasionally have more moisture in the surface air in the evening than at 2 P. M.

The seasonal range in absolute humidity depends upon the seasonal change in temperature or wind direction. For places having cold and warm seasons, the maximum occurs in the warmest season and the minimum in the coldest, and there is a difference in humidity corresponding to the contrast in temperature. For example, the vapor pressure in North Dakota averages about nine times as much in July as in January; in Nebraska, six times as great; in Oklahoma four times; in Louisiana 2¼ times; at Key West, Fla., where there is little seasonal contrast in temperature, the vapor pressure of the highest month (August) is .83 in. (21 mm.) whereas in January it is two-thirds as great (.56 in., 14 mm.). These figures indicate also that the annual range in vapor pressure increases with latitude, which is in keeping with the increase in temperature range.[144]

RELATIVE HUMIDITY.

57. *Relative humidity increases, on the average, with latitude and altitude and is greater along the coasts than inland.* In general it increases as absolute humidity decreases. The increase in relative humidity with latitude and altitude accompanies a normal decrease in temperature and hence in capacity for holding moisture. The increase with latitude on the land is illustrated along practically every meridian on Day's maps of relative humidity for the United States[145] in spite of the conspicuous influence of the western highlands on the distribution of moisture. The following annual averages from 7 A. M. and 7 P. M. for places having almost the same precipitation (between 20 and 25 inches) (508-635 mm.) illustrates the influence of latitude: Fargo, N. D., 79%; Huron, S. D., 72%; North Platte, Neb., 70%; Dodge City, Kan., 66%; Abilene, Tex., 64%. Even where the precipitation decreases notably from south to north, as in the following places, the average relative humidity increases with latitude; Chicago, 74%; Milwaukee, 75%; Escanaba, Mich., 79%; also Louisville, Ky., 69%; Indianapolis, Ind., 72%; Grand Rapids, Mich., 76%; and also St. Louis, Mo., 70%; Madison, Wis., 75%. The increase with latitude is made

[144] Computed from Figs. 4 and 5 in Dav *loc. cit.*

[145] Day, *loc. cit.*

irregular, however, by variations in the distance from the sea.[146] The average relative humidity over the sea is about 85%, while that over the continents is perhaps 60%,[147] ranging from 50% or less in the drier regions to nearly 85% along the coasts. Upon the sea, the normal relative humidity is about 82% in low latitudes and 92% in high latitudes.[148] Relative humidity does not increase normally with latitude between the equator and the centers of the Trade Wind deserts.

The increase in relative humidity with altitude is not rapid and is limited by the cloud zone, above which the air is somewhat drier. The increase is not so great as the temperature gradient would suggest because moisture is supplied only from moist surfaces at the bottom of the atmosphere and there is progressively less and less moist land at higher altitudes. Thus high altitudes often have dry air when saturated air would be expected on the basis of the normal, though often small, increase of relative humidity with altitude. Dryness is much more common on the leeward side of mountains than on the windward side. Such dryness usually is related to a foehn or is produced by an excessive settling of higher layers of air such as often cause the dispersal of clouds at night. (See Law 65.) A third way in which the air at high altitudes is sometimes made intensely dry is given in Law 53 above. This principle operates to make the air dry when in contact with the warm skin. Whenever the cold air of high altitudes and latitudes is warmed by contact with warm skin it becomes distinctly dry and causes rapid evaporation. Thus very cold air affects man like dry air because as it is warmed by contact it becomes relatively dry. This is nearly as true of cold air which was originally saturated as of air which was dry before coming in contact with man.

58. *Relative humidity increases as air ascends and decreases as it descends. Hence relative humidity is greater on windward slopes than on leeward slopes.* This is because the capacity of space for moisture decreases with the temperature. Ascending air is cooled by expansion and by accelerated radiation. Heat lost in these ways is less and less fully replaced at higher altitudes partly because of the increased distance of the air from its chief source of heat,—the surface of the earth,—and because of the interception of heat at lower levels. On the other hand, descending air is warmed by compression and by

146 In winter in cold regions, the relative humidity often increases inland accompanying the decrease in temperature inland (Hann, Handbook of Climatology, Vol. 1, p. 151).

147 Salisbury, Physiography, p. 495, 1919.

148 Waldo, Elementary Meteorology, p. 127, 1896.

coming to lower and warmer altitudes. As it is warmed it becomes relatively drier. Under favorable conditions the air becomes warmed conspicuously and is made very dry, producing a foehn.

59. *Atmospheric humidity, both absolute and relative, averages less at the earth's surface in windy areas than in calm areas otherwise similar,* because in windy areas, the moistened lower layers of air are soon mixed with or replaced by drier air from above. Upward convection is the agent which does most to prevent the surface air from being excessively humid. As water vapor is lighter than the other constituents of the surface air, moist air is forced to rise and is replaced by heavier and drier air. The height to which it can ascend is limited by condensation and by gravity. An exception to this rule of decreased humidity with increased windiness often occurs in the centers of Highs, where, in spite of slight windiness, humidity is often relatively low because of descending air.

60. *Relative humidity of the surface air averages greater by night than by day, greater in winter than in summer, greater in cool periods than in hot periods and is also greater before than after precipitation.* The lower humidity by day in summer and during hot periods is related to the higher temperatures and the greater mixing of the surface with the drier air above at those times. The warmest time of the day, year or period normally has the lowest relative humidity because the capacity of the air (space) is greatest then. The highest relative humidity usually occurs at the coldest time. However, the coldest weather of winter in mid-latitudes is not often accompanied by the highest relative humidity because such weather is often caused by a cold wind from higher latitudes or by air descending from somewhat higher altitudes, and such air is relatively dry.[149] In general, as the temperature goes up the relative humidity goes down, and *vice versa.* However, after the dew point is reached a further increase in relative humidity is impossible; instead it stays at 100% when the temperature falls still lower.

61. *In general, seasonal and diurnal ranges in relative humidity vary in harmony with range in temperature, and therefore are commonly great in arid regions and in continental interiors, and small over the sea and most snow-covered areas.* Annual range increases toward the equator, with nearness to the ocean or lakes, with aridity, with altitude (up to the cloud zone or snow-line), and with decrease in vegetation. It is also affected by cloudiness and windiness. The amplitude is several times greater on clear than on cloudy days and

[149] This condition is illustrated locally within the tropics, where the winter winds come from the north, as at Hongkong. See Claxton, *loc. cit.*

it is especially small on continuously rainy days. The range is smaller when the wind blows steadily than in times of fitful winds or calm. The increase in relative humidity before precipitation is sufficiently marked in many places to be useful in forecasting the weather.[150] Several of these kinds of variation in relative humidity are illustrated by the following figures, from Day's tables.[151] At Burlington, Vt., the average winter (December, January and February) maximum (about sunrise) and the average winter minimum (about 2 P. M.) are 79% and 67% respectively; in summer (June, July and August) 84% and 53% respectively; at St. Louis, Mo., the corresponding figures are 74% and 54% (winter) and 71% and 50% (summer); at Sheridan, Wyo., 84% and 56% (winter) and 82% and 37% (summer). Waldo gives the diurnal amplitude for the northwestern coast of Europe as 7% in December and 17% in August; for Nukuss in central Asia, 26% in December and 50% in summer.[152]

Abnormally low relative humidities occur occasionally in the surface air. Such departures are much more extreme over the land than over the sea and in dry regions than in wet. In arid regions in the United States humidities as low as 3% occasionally occur and in humid regions as low as 10%.[153] Abnormally low relative humidities are caused by a sharp rise in the temperature of the affected air. In rugged areas, foehns often cause extreme dryness. Perhaps the free-air foehn[154] is not rare in connection with cyclonic storms. The intense downward movement produces the relative dryness.

CONDENSATION.

62. *As condensation occurs whenever air is cooled below the saturation point, it is most frequent at night and in winter, except such as is due to convection which is most frequent when convection is most intense, namely during the day and in summer,* over the land. Nocturnal and winter cooling sufficient to cause condensation is due chiefly to chilling induced by loss of heat by radiation from the surface to the overlying air, or from the air downward to colder land or water. Loss of heat by conduction is important where good conductors are involved. Condensation is sometimes caused by the mixture of cold

150 Garriot, E. B., Weather Folklore and Local Weather Signs, *U. S. Weather Bureau, Bull.* 33, pp. 20-22, 1903.

151 Day, *loc. cit.*, pp. 13-61.

152 Waldo, Elementary Meteorology, p. 125, 1896.

153 Day, *loc. cit.*, p. 10. At Hongkong, where the average rainfall is 83 in. (2110 mm.) relative humidities as low as 5% have been recorded in winter. (Claxton, *loc. cit.*)

154 Brooks, C. F., A hill-top foehn, *Mo. Weather Rev.*, Vol. 47, p. 567, 1919.

air and warm air, as when a cold wind is blowing over warm water. Most clouds are caused by convection. Ascending air is cooled by expansion at the rate of 1.6 degrees F. for each 300 feet of ascent (1° C. per 103 meters), until condensation occurs.[155] Dew, frost and fog usually appear by night and disappear by day, because of the diurnal range in temperature and in relative humidity. (For clouds see Law 65, beyond.) The greater frequency of condensation in winter is illustrated at Chicago, where, in spite of the fact that much more rain falls in summer than in winter, precipitation is 30% more frequent in winter than in summer.[156]

63. *The frequency of condensation tends to increase with latitude, with humidity and with altitude,* up to the cloud level. Except where deserts are involved, cloudiness increases with latitude, though in high latitudes the clouds commonly are thin. Sealevel fogs often persist throughout the day in high latitudes, but not in low latitudes. Frost also frequently does not disappear by day in high latitudes while dew practically always disappears by day in low latitudes. Snow and rain disappear slowly in the higher latitudes. The frequency of dew and frost formation tends to increase in any latitude with increase in diurnal range. Dew seldom forms on shipboard at sea. In arid regions the relative humidity often is so low that condensation does not occur even when the diurnal range is great. The persistence of frost or fog by day in high latitudes is greatest where the diurnal range is small, as over snowfields or on the sea.

64. *The amount of condensation decreases, on the average, with latitude, except in the Trade Wind deserts, and also with altitude above a few thousand feet.* The amount of condensation depends on the absolute humidity of the air, the amount of vapor cooled, and the extent of cooling. In the rainy tropics, where the absolute humidity is great, as much as one-tenth of an inch (2.5 mm.) of dew gathers during some nights.[157] In mid-latitudes a hundredth of an inch is a heavy dew. Clouds generally decrease in thickness and density with increase in latitude and with increase in altitude above three thousand feet (900 m.). In high latitudes the sun or moon can often be seen through clouds. Indeed, in polar regions it often snows from an almost clear sky.

The normal relationship between latitude and condensation is disturbed by the distribution of atmospheric dust. Cities, with their vast

[155] Humphreys, Physics of the Air, p. 31, 1920.

[156] Cox and Armington, The Weather and Climate of Chicago, p. 168, 1914.

[157] Von Bezold, Wm., in Abbe, C., Mechanics of the Earth's Atmosphere, *Smithsonian Misc. Collect.*, p. 283, 1893.

quantities of soot and hygroscopic dust, are sites of undue condensation, and their air nearly always has more haze than is normal for the latitude. In many cities the persistent haze is called smoke, and in others, in cool moist climates, it is often a fog. This is due chiefly to the condensation upon atmospheric dust which is a better radiator than air, and thus often cools below the dewpoint. In moist regions condensation upon the cold dust particles frequently occurs, and thus the dust acts as nuclei of fog particles. If dust particles suitable to serve as nuclei are not present in sufficient abundance, considerable super-saturation may precede condensation. In nature, however, there apparently is always sufficient dust present.[158]

65. *The amount of condensation varies from time to time with variations in the intensity of temperature changes and with the humidity.* Hence dew and frost form most abundantly when the nocturnal cooling is rapid. Because of the lessened absolute humidity following condensation, the rate of dew and frost accumulation normally declines soon after the dew-point is passed. This often occurs early in the evening. There is also a marked diurnal variation in the amount of cloudiness.[159] However, as clouds are usually formed by convectional cooling rather than by cooling by radiation, the amount of condensation represented by clouds tends to vary with convection. Therefore cloudiness usually increases by day whenever convection is marked because convection increases until the warmest time of the day is reached. Upward convection often brings bodies of air to heights where the saturation point is passed. After normal convection has reached its maximum, which commonly occurs between 2 and 3 P. M., cloudiness may increase for a time because of further cooling of air brought almost to the dew point by convection. This continued cooling is facilitated by the lessened insolation which accompanies the decrease in the angle of incidence and the development of higher clouds. The sky often clears at night because of the descent of the clouds instead of becoming overcast as would be expected where the nights are cool. At night, when convection largely ceases, the clouds are pulled downward by gravity. Often when once they are descending relatively rapidly, inertia prevents their stopping until they are sufficiently warmed dynamically to evaporate the condensed moisture. The fact that the higher air is often warmer at night than the surface air, because free air cools slowly, is also of importance in this connection. The amount of condensation to form clouds also tends to vary directly with the intensity of convection according to the season. This is true

158 Shaw, W. N., Law of Saturation, *Mo. Weather Rev.*, Vol. 42, p. 198, 1914.
159 Cox and Armington, *loc. cit.*, p. 260.

in spite of the fact that the percentage of cloudiness commonly is greater in winter, when convection is least, than in mid-summer when it is greatest.[160] Winter clouds, however, are normally at low altitudes and relatively thin, their volume and mass being usually less than that of the scattered clouds of a partly cloudy summer day. In summer, when the sun is high its rays often penetrate an amount of condensed moisture sufficient to form what in winter would appear to be a cloud-cover.

PRECIPITATION: KINDS OF.

66. *Precipitation varies in kind from place to place.* While perhaps four-fifths of the world's precipitation is in the form of rain, yet in high latitudes and altitudes, snowfall is important. Moreover sleet and hail have considerable significance. In respect to rainfall, notable differences in size of drops and in intensity of fall occur. Sleet is relatively of most importance in cyclonic climates in coastal regions in fairly high latitudes. Hail, which is always associated with intense convection, is probably most frequently formed in low latitudes. However, as a result of the rapid melting during descent relatively little hail reaches the ground in tropical lowlands. Hence hail is most frequently experienced in latitudes 20°-40°, although it falls in considerable quantities in lower latitudes. For example, ten hailstorms of a destructive character were reported in a decade in latitudes 13°-16° S. near sealevel in Australia and three hailstorms occurred in Panama (latitude 9°) in a 12-year period.[161] On the other hand, several local hailstorms occur each year in subtropical Australia,[162] and in southeastern United States.

The smallest average sized raindrops probably occur in cool marine climates where the normal precipitation is a drizzle.[163] The size of characteristic drops increases in general toward the equator and with increased aridity accompanying a similar increase in the intensity of convection. As to the rate of fall, the heaviest rains occur in low latitudes, and in general there is a progressive decline poleward in the maximum rainfall received in a day or an hour.[164] This decline is

[160] *Ibid.*, p. 267.

[161] Visher, S. S., Hail in the Tropics, *Bull. Am. Meteorol. Soc.*, Vol. 3, pp. 117-118, 1922.

[162] Commonwealth Bureau of Meteorology, Charts of Hail Storms, Melbourne, 1913-18.

[163] In Netherlands, for example, four days of each normal week are classed as rainy and yet only 28 inches (711 mm.) is received in the entire year. (Kan, C. M., in Mills International Geogr., p. 219, 1907.)

[164] For the United States, see charts of maximum rainfall in 24 consecutive hours and in one hour, *Mo. Weather Rev.*, Vol. 50, p. 119, 1922.

due chiefly to a similar decrease in intensity of convection as is illustrated by the lesser frequency of thunderstorms.[165]

67. *Most places experience seasonal variations in the kind of precipitation.* Snow often falls during the winter in middle and high latitudes, while rain often falls even in polar regions in summer.[166] Hail is characteristic of the season of most intense convection, which, for all but a few points, is shortly after the period when the sun is most nearly overhead. In respect to rainfall, there normally is a seasonal variation in size of drops, in intensity of downpour and in the velocity of fall. Winter rain commonly is made up of smaller drops than summer rain, and falls more slowly and more steadily. Downpours and "cloudbursts" are to be expected at the time of most intense convection.

PLACE DISTRIBUTION.

68. *Precipitation normally is heavy on the windward slope of steep high or cool mountains in relatively warm regions* because wherever a large volume of warm moist air is cooled notably below the saturation point, much condensation occurs (See Law 54). Rapid cooling of warm air is also often accomplished by rapid convectional ascent, where insolation is intense and therefore thunderstorms yield much rain. Precipitation is much less heavy when cold air is further cooled. Hence in uniformly cold regions, mountains have much less effect than in warm regions. The steepness of the slope is significant because convectional overturning is often induced by rather low elevations possessing a steep slope on the windward side.[167] Minor causes of air cooling are chilling by a cold wind, and contact with a cold surface (without ascent). Drizzles and fogs are often formed in these ways. The heavy precipitation in the doldrum belt and by thunderstorms elsewhere, the rainy character of the windward slopes of mountains in the Trade Wind belts and elsewhere, are all illustrations of this law.[168]

69. *Precipitation decreases irregularly in amount with increase in latitude, and in effective distance from the ocean.* The average precipitation for the globe is about 20 inches (508 mm.). The heaviest rainfall on the land of any entire latitude is in the doldrum belt (80 inches (2000 mm.) or more), and the least normal precipitation is perhaps in the polar regions (less than 10 inches; 250 mm.). While

[165] *Ibid.*, p. 122, Distribution of Thunderstorms in the United States.

[166] Stefansson, V., The Friendly Arctic, 1921.

[167] The importance of the inclination of the slope is emphasized by Pockels, F., Precipitation on Mountain Slopes (1901) translated in C. Abbe third series of the Mechanic of the Earth's Atmosphere, *Smithsonian Collections*, No. 1869, p. 101, 1910.

[168] See Laws 54 and 71 for concrete illustrations.

the Sahara and many other parts of the Trade Wind belts receive no more precipitation than do the polar regions, the average for the Trade Wind belts is raised notably by the precipitation received on the windward slopes, as is illustrated in Law 54 above. The scanty precipitation in polar regions, as at high altitudes, is due largely to the small amount of moisture in the cold air, but the slight convection there is also a factor. The poleward decrease in precipitation is illustrated on all continents.[169] The decrease with latitude is at a higher rate on the continents than on the ocean, for although in the tropics more rain falls on the land than on the sea, the reverse is true in high latitudes.[170] Not only is there a decrease in total rainfall, but there is a corresponding decrease in intensity. In Australia, for example, the number of days on which 5 inches (127 mm.) or more of rain has fallen, decreases steadily and sharply poleward.[171] The same occurs in the United States[172] and elsewhere, except where east-west mountain ranges, such as the Himalayas, form complicating factors by causing marked condensation. All the records of 30 inches (760 mm.) or more of rainfall within 24 hours are from tropical latitudes, as are nearly all records of falls in excess of 10 inches (254 mm.) in 24 hours.[173] In the United States, for example, in twenty years the only areas receiving over 10 inches (254 mm.) in 24 consecutive hours were along the Gulf Coast. No area in the northern third of the country received over 6 inches (150 mm.) while nearly five-sixths of the northern border had an extreme maximum of less than 4 inches (100 mm.).[174]

70. *Precipitation increases with altitude to moderate heights and then decreases steadily and sharply until at the height of 2 or 3 miles (3-5 km.) it is slight.* The maximum precipitation on mountains takes place at an elevation of about 3300 ft. (1000 m.) in the tropics, and about 4500-5000 ft. (1370-1520 m.) in mid-latitudes.[175] The altitude of the zone of maximum precipitation depends upon the relative humidity and temperature of ascending air. Therefore the height

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169 See Herbertson's rainfall maps in Bartholomew's Physical Atlas, 1899.

170 Moore, John, Meteorology, p. 223, 1910 (quoting Herbertson).

171 See lists of heavy rainfalls, Hunt, H. A., The Climate and Meteorology of Australia, Official Yearbook, pp. 59-63, 1920.

172 See Precipitation Section of Atlas of American Agriculture (partly reproduced in *Mo. Weather Rev.*, Vol. 50, pp. 117-124, 1922.

173 Visher, S. S., Variability vs. Uniformity in the Tropics, *Scientific Monthly*, Vol. 15, pp. 28-31, 1922.

174 Precipitation Section of Atlas of American Agriculture, *loc. cit.*

175 Henry, A. J., Increase of Precipitation with Altitude, *Mo. Weather Rev.*, Vol. 47, pp. 33-41, 1919. A thoroughgoing exposition of the subject.

fluctuates with the seasons, being lowest in winter, when low temperatures cause prompter precipitation, than in summer when the relative humidity at any given level is less than in winter.[176] The rate of increase up to the zone of maximum rainfall varies with the total rainfall, being 100 in. for each 1000 ft. (830 mm. per 100 m.) for example, in portions of the Himalayas, 40 in. per 1000 ft. (333 mm. per 100 m.) in Java, and only 2 in. per 1000 ft. (17 mm. per 100 m.) in arid portions of Africa and South America.[177] However, when expressed in percentages, the rate of increase is somewhat similar even in such diverse cases as these, for the increase with each 1000 or 1500 ft. (300 or 450 m.) of altitude is approximately equal to the total rainfall at the base of the slope. Above the zone of maximum rainfall, the decrease is rapid. At high altitudes, it is chiefly in the form of "finely pulverized snow or a drizzle."[178]

71. *Local contrasts in the amount of rainfall are greater in tropical than in higher latitudes among topographically similar places, with the exception of the doldrums.* Local contrasts in humidity, evaporation and wind likewise commonly decrease with latitude. It is probable that tropical, mountainous, oceanic islands have the greatest local climatic differentiation while polar regions have the least. Near the poles even a high mountain causes relatively little local differentiation. In low latitudes one side of many moderate elevations is distinctly more humid than the opposite side, and there is a sudden change in humidity and precipitation with altitude even on the windward slope. Both wind direction and altitude influence the rainfall of many small areas. For instance, within the city of Honolulu the average rainfall ranges from less than 25 in. (635 mm.) to over 90 in. (2290 mm.) at a place of similar elevation only 5 miles (8 km.) distant. Also within 4 miles (6 km.) of the central station with its 31 in. (790 mm.) of rain there is a station with an elevation of 1360 ft. (414 m.) and an average rainfall of 106 in. (2700 mm.). On another of the Hawaiian Islands, Kauai, apparently the rainiest official rainfall station on the globe and with an average of over 476 in. (12.2 m.), is 11 miles (18 km.) distant from a station which receives less than 20 in. (508 mm.).[179] In middle and high latitudes there normally is relatively little contrast in rainfall between the sides of single ranges since the winds come into cyclonic depressions from all directions in

[176] Hann, J., Lehrbuch der Meteorologie, 3rd ed., 1915.

[177] Henry, *loc. cit.*, p. 34.

[178] Hann, Lehrbuch, quoted by Henry, *loc. cit.*

[179] Climatological Data, Hawaiian Section, 1922, supplemented by annual reports for 1919-21 inclusive.

turn, instead of chiefly from one direction as in the tropics. Hence one side normally is very dry in higher latitudes only in case the winds are prevented by some other range from bringing moisture to it. Consider the relatively slight contrast in rainfall on the different sides of the Appalachians, Alps and Caucasus, in comparison with the great contrasts found on most tropical ranges. The local change in rainfall, which accompanies change in altitude, also is less in higher latitudes than in low because there is less change in capacity for moisture when cool air is further cooled than when warm air is cooled a like amount by being forced to rise.

Other causes of greater local differentiation in climate in low latitudes than in high are (a) the steeper vertical temperature gradient, so that corresponding changes in altitude produce greater changes of temperature in the tropics than in high latitudes, especially at night, (b) the greater tendency for calms to develop on lowlands at night in the tropics than in higher latitudes (See Law 48, under winds). It is partly for this reason that even moderately low ridges in the tropics have an appreciably different nocturnal climate from nearby plains, while there is less differentiation between ridge and plain in higher latitudes. (c) A third factor which causes greater local contrast in low than in higher latitudes is the sea breeze, which is much commoner in warm than in cool regions, and which gives to a narrow littoral strip in the tropics a climate distinctly different throughout the year from that found only a short distance inland. Sea breezes blow almost every day upon many tropical coasts because the land becomes very much warmer than the water almost every day, instead of only during hot spells in summer, as in high latitudes. Other sorts of climatic localization and their chief causes are discussed more fully elsewhere.[180]

DIURNAL AND SEASONAL DISTRIBUTION.

72. *Precipitation takes places more easily in winter than in summer and at night than by day* because precipitation occurs whenever drops, flakes or pellets are formed which are too heavy to be sustained in the air by the rising air currents. Such ascending currents are weaker in winter and at night than in summer and during the day. Precipitation reaches the surface whenever the particles are not evaporated as they fall. Much summer rain, especially above deserts, fails to reach the earth. Hence additional reasons why precipitation reaches the surface more readily in winter than in summer, and also more

[180] Visher, S. S., Local Climates in the Tropics, *Bull. Am. Meteorol. Soc.*, Vol. 3, pp. 119-121, 1922.

easily at night than by day, are because the clouds are usually lower and the lower air is more humid in the cooler than in the warmer times. Ease of precipitation does not however imply amount of precipitation, for in spite of the fact that precipitation is often induced in winter by barometric influences which would not yield precipitation in summer,[181] the total amount of precipitation received in summer is greater than that received in winter over a large share of the earth. One result of the greater ease with which precipitation takes place in winter than in summer is the fact that snow storms normally last longer than rainstorms, in spite of the fact that cyclonic storms usually move more rapidly in winter than in summer.[182] At Chicago, the average snow storm lasts 7.5 hours while the average rain storm lasts 3.9 hours.[183]

73. *Most places have a wet season and a dry season* because the distribution of precipitation throughout the year depends on (1) comparative temperature of land and sea, (2) wind direction and character, (3) intensity of insolation and hence of convection, (4) frequency of temperature changes passing the dew-point. When land is notably cooler than the sea, precipitation on the land is to be expected if the wind is off the sea. In such a wind, the air in contact with the colder land surface is cooled by radiation and conduction. Another part is cooled by being forced to rise over air piled up by the much greater friction on land than on the sea. However, the rise produced in this way is seldom sufficient in itself to cause heavy precipitation. Cyclonic and irregular winds bring more precipitation to most plains than do steady winds. Intense insolation normally produces active evaporation, strong convection currents and subsequent thunderstorms. Variations in temperature from above the saturation point to those notably below that point cause precipitation.[184]

The season during which an area normally receives the most precipitation depends upon which of the four influences enumerated above is most significant. In general the warmer regions receive most of their precipitation shortly after the date when the sun is overhead or most nearly so, because of the intensified convection. Cold regions also receive most precipitation in their warmer season because during their colder season the air can contain little moisture and hence can give up little. Furthermore, there is little moisture available for

[181] Henry and others, Weather Forecasting in the United States, *loc. cit.*

[182] *Ibid.*

[183] Cox and Armington, *loc. cit.*, pp. 185-191.

[184] Unless such temperatures are confined to the air in contact with the surface of the land, when dew or frost formation occurs instead of precipitation.

precipitation in cold areas because winds blowing toward them have lost much of their moisture before going far inland. The shifting of the wind belts with the seasons is the dominating influence in seasonal rainfall variations for many subtropical and subequatorial areas. The winter season is the wet one on western coasts in the subtropical belt. Interior plains in mid-latitudes have more precipitation in spring and early summer than in any other four or five months.[185] Raininess in spring is a result of (1) the release of moisture accumulated on and in the ground during the winter, (2) the changeableness of the temperatures and (3) the steep temperature gradient upward. The summer rains result chiefly from increased convection and frequent reprecipitation and especially from the indraught of moisture-laden air from the sea, induced by high continental temperatures. Between the spring and the summer rains there is often a drought, frequently in June in mid-latitudes in the northern hemisphere. Winter droughts in continental interiors are due in part to the faster movement of the Lows at that season but chiefly to the fact that condensation then takes place nearer the coast than it does in summer, because of the rapid fall in temperature inland from the coast in winter.

74. *The seasonal range in rainfall varies with latitude and with relation to the ocean.* The contrast between the amounts of precipitation received in the wet season and in the dry is greater in the tropics than in middle latitudes. Indeed it seemingly varies inversely with the latitude from the edge of the doldrums to the polar regions, among places otherwise similar. The range also normally increases from the coast inland, and it probably averages less on windward than on leeward coasts. The average increase inland is largely due to the scanty winter rainfall characteristic of continental interiors. (See preceding law.) On the average windward coasts have less range than leeward coasts because the latter get a large share of their moisture from cyclonic winds which are less regular in occurrence and strength than the planetary winds. However those portions of the lee coasts which experience strong monsoons normally have well defined wet and dry seasons. Evidence showing the greater seasonal contrast in rainfall in low than in middle latitudes is given elsewhere.[186] Briefly, much more of the tropics possesses a large contrast among the monthly totals of rainfall than is the case in middle latitudes. For example, twice as large a percentage of their area receives 20% more rain in the wettest than in the driest month. In respect to greater and lesser

[185] For maps of the season of rainfall see Bartholomew, *loc. cit.*

[186] Visher, S. S., Variability vs. Uniformity in the Tropics, *Scientific Monthly*, Vol. 15, pp. 23-35, 1922, and The Variability of Tropical Climates, *Meteorol. Mag.*, London, Vol. 58, pp. 121-125, 154-159, 178-179, 1923.

percentage ranges also, the tropics are inferior to the higher latitudes. The great seasonal range in the low latitudes is related to the fact that most tropical localities are crossed by desiccating winds during part of the year (the Trades or land monsoons), while in other months conditions are favorable for rain, as when the doldrums pass, or when the ocean monsoon prevails, or in Mediterranean climates, when the Westerlies prevail. In higher latitudes rainfall conditions are on the average more uniform throughout the year, not only because of the general lack of drying winds, but also because there is greater uniformity in the effects of cyclonic disturbances. (See Law 80.)

75. *The frequency of precipitation tends to increase directly with the annual amount but inversely with the monthly range in precipitation* except in the monsoon areas. In other words, places with heavy rainfall are usually places of frequent rains, and wet years are years of many rainy days, on the average. However, in regions of marked seasonal distribution of rainfall, precipitation occurs fewer times in a year than in places where rainfall seasons are less marked. Since in general the seasonal range is greater in low than in high latitudes, the frequency of rain tends to be less in low latitudes than in high, wherever similar annual amounts are received. However, on windward slopes in the Trade Wind belt the frequency is high as is also the annual amount, while the monthly range is comparatively low.[187] A special illustration of the frequency of precipitation is the duration of rainfall, which increases with the latitude.[188]

76 *There are for most places two diurnal maxima and two minima for precipitation in regard to both amount and frequency. The maxima usually are at 2-5 P. M. and 3-6 A. M., and the minima at 9-12 A. M. and 11 P. M.-2 A. M. respectively.* The afternoon maximum coincides with or follows the period of most intense convection. Sometimes the afternoon maximum is delayed until early evening. The early morning maximum is caused by the marked turnover which often occurs then as a result of the excessive cooling of air above the surface layers. The forenoon minimum and the midnight minimum occur at times when heating and cooling respectively are taking place steadily but have not gone far enough to cause marked convection or overturning.[189]

There is considerable variation from place to place, and also from season to season in the precipitation yielded by the nocturnal and

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187 See Supan: Bartholomew's Physical Atlas: Meteorology, p. 19, 1899.

188 Hann, *loc. cit.*, p. 61.

189 For discussion of diurnal distribution of rainfall see Hann, Lehrbuch, *loc. cit.*, pp. 338-346; and Cox and Armington, *loc. cit.;* and Claxton, *loc. cit.*

afternoon maximum. In the southeastern part of the United States, and in the arid west, much more rain is received from the afternoon maximum. Indeed nocturnal rain is relatively uncommon there. In the Northeastern States, on the other hand, while the afternoon maximum predominates, it yields only a little more rain than the nocturnal maximum. A different condition prevails over a considerable area in the central part of the United States, for there more summer rainfall is received between 8 P. M. and 8 A. M. than in the other 12 hours. In the center of this area, southern Nebraska, the "nocturnal" precipitation makes up 65% of the total.[190] In the British Isles more rain falls at night than by day during the winter and the reverse is true in summer, though this condition is partly due to the corresponding seasonal difference in the length of day and night.[191] In the rainy tropics, although rain is very common from 3-6 A. M., afternoon showers are expected daily.[192]

VARIABILITY.

77. *Variability in the amount of precipitation increases with aridity,* because, (1) the chances of a constant supply of atmospheric moisture reaching an area decreases with an increase in the remoteness of that area from its source of moisture. Little moisture is carried in one continuous journey from the ocean to any moderately inaccessible point and precipitated there. Instead most moisture is precipitated and evaporated repeatedly, and sometimes it is carried away from the ocean and sometimes toward it by the winds and streams. In its journey toward the drier regions, the total supply of moisture is decreased by runoff. (2) In humid regions a considerable portion of any excess rainfall returns to the sea as runoff, whereas in arid or semi-arid regions an unusually heavy, widespread rainfall may disturb the normal moisture conditions for a considerable period. (3) The abundant soil moisture, dense vegetation, high water-table and standing water present in humid regions act as a stabilizer of atmospheric moisture conditions, whereas the relative lack of these influences in more arid regions permits greater variations in moisture conditions.[193]

78. *The amount of precipitation received by an area during corresponding intervals of time varies irregularly.* One summer or year

[190] Kincer, J. B., Day-time and Night-time Precipitation (in the U. S.) and their Economic Significance. *Mo. Weather Rev.*, Vol. 44, pp. 628-632, 1916. A summary of this paper with interpretations is given by Humphreys, *Ibid*, Vol. 49, pp. 350-351, 1921.

[191] Moore, Sir John, Meteorology, p. 262, 1910.

[192] Ward, Climate, *loc. cit.*, p. 82.

[193] Visher, S. S., Rainfall in the Great Plains in The Geography of South Dakota, *loc. cit.*, pp. 60-67.

may be wet and the next dry, or several wet years may be followed by several dry ones. Most fluctuations in precipitation in middle latitudes are related to differences in the paths, the intensity, the speed and the size of Lows, for these cyclonic disturbances cause most of the rainfall. Storm tracks are affected by anomalous variations in the temperature of continental and oceanic areas. Lows often tend to move toward abnormally warm areas. The rainfall in low latitudes, as well as in middle latitudes is closely related to the passage of low pressure areas.[194] A special feature of the irregular fluctuations in the amount of precipitation is the tendency for wet periods to perpetuate themselves, and for droughts to continue. This is perhaps never a dominating influence but undoubtedly is sometimes significant. Abundant surface waters and a high water-table certainly are more conducive to a high atmospheric humidity than are parched soil and dry lakebeds. Conversely, "All signs of rain fail in dry weather." The importance of soil and surface water in supplying moisture for precipitation is suggested by Murray's estimate that only one-fourth or one-fifth of the precipitation on the land is returned to the ocean by the rivers.[195] In some level areas the proportion of runoff is much less; for example it is only about one-twentieth for the basin of the Red River of the North. If three-fourths or more of all the precipitation on the land is evaporated locally, as seems likely, much of it probably is reprecipitated on the land. Areas remote from the ocean probably receive much more than half their precipitation in this way.

79. *Cycles of rainfall occur in many places.* Many of these are quite irregular in length and in intensity and no doubt many are due largely to the semi-periodic return, called for by the law of chance, of similar combinations of atmospheric conditions, as when analogous storms travel along similar paths. However a part of the semi-periodic fluctuation appears to be related to variations in the activity of the sun, for a correlation between sunspot periods and fluctuations in precipitation seems to be established.[196] In general continental

[194] Taylor, G., The Australian Environment especially as controlled by rainfall, 1918 (summarized by Visher in *Mo. Weather Rev.*, Vol. 47, pp. 490-494, 1919), and Visher, S. S., Australian Hurricanes and Related Tropical Cyclones, *Bull. Commonwealth Bur. of Meteorol.*, 1923; for the U. S. see Henry and others, Weather Forecasting in the U. S., *loc. cit.* and especially Henry, A. J., Secular Variation of Precipitation in the United States, *Bull. Amer. Geogr. Soc.*, Vol. 46, pp. 192-201, 1914.

[195] Quoted by Tarr-Martin, Physiography, p. 104.

[196] Brooks, C. E. P., The Secular Variation in Climate, *Geogr. Rev.*, Vol. 11, pp. 120-137, 1921; and Clements, F. E., Drought Periods and Climatic Cycles, *Ecology*, Vol. 2, pp. 181-188, 1921. See however a review and discussion of Clement's paper by Henry, A. J., *Mo. Weather Rev.*, Vol. 50, pp. 127-131, 1922.

interiors receive more rainfall when the sunspots are increasing than when they are decreasing, whereas marine climates, and some others, respond in the opposite way. The fact that different areas respond in opposite ways to changed solar activity has done much to conceal the relationship between solar changes and terrestrial weather, for wherever the rainfall of large regions are compared, the excessive rainfall received in one part may offset the deficient rainfall of another part. Another disturbing practice has been the comparison of the rainfall records of the single year when the sun's spottedness reached the maximum with the records of the single year when the spottedness was at a minimum. It is a well established fact that a single year is not so good a basis for comparison as the average of a number of years. When the rainfall data for the several years of increasing spottedness are compared with those of the years of decreasing spottedness, rather sharp contrasts become evident, which can be explained fairly well by shifts in the average storm paths, and by variations in the storms themselves.[197]

The anomalous temperature and pressures which develop from time to time over critical portions of the ocean and land are quite possibly induced indirectly by variations in solar activity. As noted in the previous law, storm paths are strongly affected by the development of such abnormal conditions. Likewise there appears to be a general shift in storm paths within the sunspot cycle. When the sun is increasing in activity, the main storm track shifts poleward,[198] with resulting changes in rainfall in a rather wide though not straight belt. The character of the change differs, however, within this belt, for at the same time that the rainfall is increasing toward the northern margin, it is decreasing at the southern.

80. *Dependability of rainfall is greater in middle than in low latitudes, and tends to increase with latitude, among places receiving similar amounts.* Most tropical cities, concerning which data are available, received three or more times as much rain in an especially wet year as in an especially dry one, while in mid-latitudes, few places receive twice as much. Indeed in fairly high latitudes in western Europe the range seldom is as great as 50%. This decrease in absolute range is the more notable because it accompanies a general decrease in total rainfall. With the smaller total annual amounts of precipitation characteristic of high latitudes, it is easier to obtain large

[197] For a summary of evidence concerning changes in precipitation see Huntington, Earth and Sun, 1923 and Huntington and Visher, Climatic Changes, *loc. cit.*, pp. 53, 58, 59 and 93.

[198] Huntington, Earth and Sun, *loc. cit.*

percentage ranges than it is with the larger totals characteristic of low latitudes. Many illustrations of widespread and marked fluctuations in annual rainfall in tropical regions are given elsewhere.[199] A few may be mentioned here. The average rainfall at the 150 rainfall stations scattered over the Hawaiian Islands was 54.5 inches (1284 mm.) for 1918 but was 112.9 inches (2868 mm.) for 1919. Equatorial Singapore has received five times as much rainfall in one year as in another; equatorial Oceanic Island (longitude 169° E.) received 8 times as much rain in 1905 as in 1909 (19.6 inches vs. 158.9 inches; 500 mm. vs. 4040 mm.); Malden Island (latitude 4° S., longitude 155° W.), 2,000 miles (3220 km.) to the eastward, received 16 times as much in 1905 as in 1908 (3.9 in. vs. 63.4 in.; 99 mm. vs. 1610 mm.).

Not only is there a wider range in the annual rainfall in low latitudes, but excessive falls within short periods are of greater magnitude and are more frequent in tropical latitudes than in higher latitudes. (See Law 69.) On the other hand, droughts likewise are more frequent and protracted in tropical latitudes than in higher latitudes having similar average rainfalls. In parts of middle latitudes, where the normal rainfall is 40 inches (1000 mm.) or more, periods of a month without precipitation are very rare during the normal rainy season, while in the tropics even where the average rainfall is over 80 inches (2000 mm.) as in the Philippines, periods of several weeks with no rain are not very rare.[200]

The greater variation in annual rainfall in tropical latitudes than in higher latitudes appears to be related to annual contrasts in storminess. For example, some tropical localities are visited by several times as many hurricanes in one year as in another. In regions where hurricanes are almost lacking, as is the case of the equatorial stations mentioned above, there is nevertheless a sharp contrast in the annual number of disturbances produced by mild local storms or by distant hurricanes. In higher latitudes there is greater uniformity both in the number and in the severity of storms. This is partly because many of the tropical storms move poleward, where the meridians converge, and then move eastward, perhaps, nearly encircling the globe. Thus there are many more storms in high latitudes than in low. Storms are less severe in high latitudes than in low probably because they are accompanied by less condensation of water vapor. The energy

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199 Visher, S. S., Variation vs. Uniformity, *loc. cit.*, and Tropical Climates from an Ecological Viewpoint, *Ecology*, Vol. 4, pp. 1-10, Jan., 1923.

200 Coronas, The Climate and Weather of the Philippines (Official), pp. 111-123, 1920.

liberated at condensation is the great source of the storm's energy. The cool temperatures characteristic of high latitudes permit a smaller moisture content than prevails in tropical latitudes. Hence cyclonic disturbances cause less condensation in high latitudes than in low, and therefore possess less energy.

TITLES AND ABSTRACTS OF PAPERS

Ann Arbor, 1922

Harlan H. Barrows.

Presidential Address, Geography as Human Ecology.—Printed in full, Annals, March, 1923.

M. Aurosseau.

The Geographic Study of Population Groups.

The different kinds of population groups were briefly described, and the trend of their evolution into the groups of the present day discussed. The principle was deduced that the character and development of the group are the result of interaction between the group and its origin, and it was shown that overpopulation of the region tends to be adjusted by revolutionary changes in the method of occupation. The supplanting of ruralism by urbanism at the present time, and the accompanying evolution of the region of simple and uniform production is believed to have assisted the rise of the conurbations. These in turn have made the world as a whole their area of supply, and foreshadow a period of world-overpopulation, which is an extension of the regional overpopulation of past times.

H. H. Barrows.

Memorial of Rollin D. Salisbury.

O. E. Baker.

The Agriculture of the Great Plains Regions.—Printed in full, Annals, September, 1923.

Nels A. Bengtson.

The Petroleum Industry of Ecuador.—Read by Title

William Bowie.

The Board of Surveys and Maps of the Federal Government.

The Board of Surveys and Maps of the Federal Government was created by Executive Order on December 30, 1919. This action was

based on an investigation made at a conference of representatives of the map making and map using organizations of the government called together by the President of the United States, in response to a recommendation of the Engineering Council. The Board was organized on January 10, 1920, and has continued in active operation since that time.

Prior to the creation of the Board there was little or no attempt by the various bureaus to make their work fit into that done by other organizations. This has been changed. There has been no attempt to reorganize the government mapping and surveying bureaus as this has not been considered to be a function of the Board. Standards have been adopted for the performance of various classes of work and the meeting of the representatives of the member organizations in conference at least once a month and the discussion of the surveying and mapping problems has resulted in efforts by each bureau to do its utmost to help the other organizations.

Aside from coordinating the work of the various bureaus and setting standards of accuracy for the several classes of work, the Board has studied carefully the problem of completing the topographic map of the country within a reasonable time.

The more the question of topographic mapping is studied, the more evident it is that the work should be carried on much more rapidly than at present. There is scarcely a human activity, including topographic research, that is not dependent to a certain extent on the knowledge of the configuration of the ground and geographic location of topographic features. In the interest of the commercial and industrial development of the country and for military protection, it is believed by the Board that greater activity should be shown in the completion of the topographic map of the country.

Isaiah Bowman.

The Political Geography of the Mohammedan Realm.

The Mohammedan World occupies a great area—at least three times that of the United States—extending from western Siberia southward into India and westward across Africa to the Atlantic. Bosnia represents its farthest outpost in Europe. By superimposing the line representing the limits of the Mohammedan World upon the various maps in Finch and Baker's *Geography of the World's Agriculture* and maps of mineral resources in *World Atlas of Commercial Geography, Part I, Distribution of Mineral Production,* published by the U. S. Geological Survey, it is possible to arrive at an understanding of the material strength of the Mohammedan World as its stands today. The standards

of power have completely changed since well organized mounted horsemen invaded Europe from the grasslands and deserts about the Eastern border of the Christian World. Coal and steel and the modern battleship put the Mohammedan World on a totally different plane. The main purpose of the paper was to assess the material power of the Mohammedan World and to contrast it with the main sources of power in the Christian World. If there is disunion among the score and more of nations that comprise Christian Europe, there is also serious disunion among the Mohammedans themselves. The historical manifestations of disunion and the modern tendency toward it were both reviewed and the conclusion reached that, unless Christian civilization fails altogether and disunion goes to far greater extremes, there is no cause for Europe to fear a Mohammedan invasion, though there is serious danger of repeated weakening quarrels.

Robert M. Brown.

Changing Occupations in the United States.—Read by Title.

Charles C. Colby.

The California Raisin Industry.

As the raisin industry in California developed to its present size and prosperity numerous adjustments to the natural environment were made. In making these adjustments biological and other scientific principles were utilized, a special type of economic organization was introduced, and existing social and political conditions were modified. The present analysis of this industry shows (1) that the industry is localized in the east-central part of the San Joaquin Valley because there the requisite climatic conditions for the production of raisins on a commercial basis exist; (2) that the vineyards are irregularly spaced within the producing district as the result of variations in topography, soil, water supply, and drainage, on the piedmont alluvial plain where the industry is located; (3) that years of experimentation were necessary before the situations best suited to the requirements of the several varieties of raisin grapes were known; (4) that in keeping Phylloxera and other enemies of the vine under control, drastic import and other regulations have been enforced and agricultural practices based on biological principles introduced; (5) that important statutes were written into the laws of the state to settle the conflicting claims of the ranchers during the period when the irrigation systems were constructed; these conflicting claims being in part due to the ease with which the distributaries of the several rivers were tapped for irrigation; (6) that the present prosperous condition of the

industry was attained only when a carefully coordinated system of producing and marketing the crop was established—a system adapted to the fact that the raisin producing district and the principal markets for the crop are more than 2,000 miles apart.

Nevin M. Fenneman.

The Work of the National Research Council.

The National Research Council is concerned primarily with bettering the conditions which underlie and surround research, and only secondarily with prosecuting researches on particular problems. Emphasis is laid on the fact that the Research Council is merely a *mode of cooperation* and not an institution to conduct research. Geographers are guarded against the assumption that the Research Council is directly financing investigations. Most of the money paid out for researches under the charge of the Research Council is solicited for the particular purpose in hand, largely by those who originate the project or are engaged in the investigation. The sources of these donations are here examined and classified in order to assist geographers in estimating their own opportunities. Aside from the question of financial support, the Council offers great advantages for cooperation, by supporting a central office which acts as a clearing house for information, conducts correspondence, keeps records and in general performs most of the drudgery which otherwise causes so much promising cooperative work to fail.

J. Paul Goode.

The Evil Mercator.—Read by Title.

Ellsworth Huntington.

Influenza, an Example of Statistical Geography.

One of the main objects of geography is to discover the relative effects of different physical factors in determining the location of all sorts of phenomena. It is becoming increasingly evident that in order to do this careful statistical analysis is necessary. The Committee on the Atmosphere and Man, appointed by the National Research Council, has recently made a study of influenza. Previous studies by means of the method of partial correlation coefficients has shown that various environmental factors, such as density of population, had no effect on the geographical distribution of the disease. Further studies by the same method bring out an important relationship to the conditions of the weather immediately preceding the epidemic and at the time of its maximum severity. An analysis of the results by means

of partial correlation coefficients shows that geographical factors were the main factors in determining whether the epidemic should be severe or light in different parts of the country.

W. L. G. Joerg.

The Use of Airplane Photography in City Geography.

The paper dealt mainly with that fundamental element in the study of geography, city maps on an adequate scale, say 1:15,000, which show the built-up areas, and the means now afforded by airplane photography to supply that element easily. This new means is especially valuable in the study of American cities, of which, as a rule, maps showing the built-up areas have not been available other than the topographic sheets of the U. S. Geological Survey, whose scales are too small for the "internal" study of a city, or real estate atlases, whose scales are so large that reduction and the necessary generalizations are laborious processes.

Douglas Johnson.

Some Analogous Shorelines of Partially Submerged Triassic Lowlands.—Read by Title.

The Triassic Lowlands of the Bay of Fundy region, the New Haven region, and the New York-New Jersey region have been partially submerged; the first extensively, the second slightly, and the third to an intermediate degree. Though the resulting shorelines are superficially very different in appearance, they present certain striking analogies due to similarity of physiographic history.

Wellington D. Jones.

A Classification of Climate for Use in Economic Geography.

A manuscript map was exhibited and described.

Louis C. Karpinski.—(By invitation of the Council.)

The Contribution of Mathematicians and Astronomers to Scientific Cartography.

The three fundamental problems of scientific cartography are the location of points on the earth's surface, the determination of the size and shape of the earth, and the representation on a plane surface of the observed facts. All of these problems require the services of the mathematician, the astronomer, the instrument maker as well as that of the geographer.

The ancient Babylonians contributed a fine start to scientific geography, particularly the 360 degrees in the circle and ideas connected

with the location of the position of the stars. The Greeks gave a scientific system of astronomy and of geography, culminating in the geography and the maps of Ptolemy. The Arabs made notable advance on the mathematical side, in explorations, in the recording of latitude and longitude, in perfecting and inventing instruments of observation, in the development of tables, and in cartography. The European translators in the twelfth century made the work of the Greeks and Arabs available. Scientific cartography became a matter of national concern first to the Spanish and the Portuguese and later to the Dutch, the English and the French. With the collaboration of astronomers, surveyors, mathematicians, geographers, physicists, and instrument makers, the necessary data for scientific cartography were finally made available at the beginning of the eighteenth century.

Up to the eighteenth century the two great errors of Ptolemy's maps continued on practically all the widely used maps. These two errors were in depicting the Mediterranean Sea too wide by 20 degrees and an even greater error in the width of Asia and Europe combined. The invention of the telescope, the pendulum clock, and the chronometer, made possible the corrections of these errors, through astronomical observations and by astronomical methods.

Any serious study of the development of a modern map reveals then that in part we are truly the heirs of all the ages. The maps come to us as a part of our heritage of science. The map is the achievement of countless scientists of ages past, of all nationalities seeking to record their comprehension of the universe about them. The map of the world as we have it today is a symbol of the unity of the sciences; the map is a symbol of the progress of science as the product of scholars of every land and of every age.

J. B. Kincer.

Climate of the Great Plains as a Factor in their Utilization.—Printed in full, ANNALS, June, 1923.

A. K. Lobeck.

Physiographic Divisions of Europe.—Read by Title.

The detached nature of the various similar physiographic provinces of Europe necessitates a division of features on a basis somewhat different from that used in the case of the United States where each province is a continuous unit. This detachment of related parts is due to down-dropping or inwarping of large areas or the uplifting of separate blocks so as to produce a checkerboard arrangement of highlands and lowlands.

Four main groups of features may be distinguished. First, is the Northwestern Highland belt with its associated downdropped lowlands. This area includes the highlands of Scotland, Ireland, Scandinavia, as well as those of Wales and Brittany. The associated lowlands represented by the Central Lowlands of Scotland. Other lowlands are now submerged.

The second large group consists of the Central Plains of Europe extending from southern France to Russia. This is practically a continuous belt but may readily be subdivided into several basins, lowlands, or plateau areas.

The third group includes the Massives of Central Europe with their associated lowlands. Its parts resemble the members of the Northwest highlands in physiographic character. The Spanish Meseta, the Central Upland of France, the Vosges, Black Forest, Slate Mountains, the Bohemian Massive are all examples of the Massives; the Rhine Graben and the Thuringian Basin are types of the downdropped segments.

Finally, the fourth group involves the youngest mountains of Europe with certain included lowlands and massives. This can be termed the Alpine system. It is more continuous than the older massive belts and can be traced in great swinging areas from the Pyrenees to the Caucasus and Asia Minor. The Po Basin and the Hungarian Plain are included basins; the Rhodope Mountains constitute a massive block hemmed in by the folded ranges.

K. C. McMurry.—(Introduced by Carl O. Sauer.)

The Economy of Electric Power in the Southern Appalachians.

An increase of 51 per cent in power equipment from 1909 to 1919 is a significant measure of industrial growth in North and South Carolina, Georgia, Alabama and Tennessee. The increase has been almost wholly due to added electric power equipment, in large part hydro-electric.

The several large power companies which furnish the bulk of electric power operate about 1,000,000 hydro-electric horsepower and 400,000 steam-electric horsepower. The hydro-electric plants range from installations of more than 100,000 horsepower to small plants of a few hundred horsepower. The plants are widely distributed over the area and all the large rivers are involved. The largest steam-electric plant, developing 80,000 horsepower is located at Muscle Shoals, while smaller plants are scattered throughout the system.

Hydro-electric and steam-electric plants supplement and are necessary to each other in this system. The flow of streams is irregular

and the steam plants, furnishing power during low water, lead to a more efficient and larger development of hydro-electric power than would be possible without them. Of equal importance is efficient use of power in the inter-connection of systems, by which it is possible to transmit power from end to end of the region, a distance of more than 600 miles. This makes possible a single power plant, for neither supply of power nor load fluctuates equally throughout the whole area.

The cotton manufacturing industry uses the largest amount of electric power, but nearly all industries are coming more and more to the use of this type of power. While a large amount of hydro-electric power is now developed, there is much more available, and eventually it seems likely that three to four times as much power of this type will be utilized as at present.

Curtis F. Marbut.

Soils of the Great Plains.—Printed in full, ANNALS, June, 1923.

A. E. Parkins.

The Temperature Region Map.

The paper briefly sketched the development of the idea of temperature regions and compared the temperature region maps of various authors. The map which accompanied the paper, while using the Herbertson scheme of classifying months, is original in that it is based on data of some 2,500 statements, distributed over the world. The paper discussed the distribution of the ten temperature regions and showed, by a second map, in which surface isotherms for the hottest and the coldest months were superimposed, how the migration of the isotherms give origin to the different regions The writer makes the following claims for the temperature region map:

1. It is a surface temperature map, as well as a surface temperature region map. It avoids objections geographers have to sea-level isothermal maps.
2. It shows the surface isotherms for both the hottest and the coldest months superimposed on one map. It shows the three most significant isotherms in geography. It enables one to study the speed of migration of these three isotherms. It shows temperature conditions for the hottest and coldest months and thus avoids objections geographers have to annual temperature maps.
3. It shows altitude and oceanic effects as well as any temperature map.
4. It can be used as a base map in delimiting climatic provinces.
5. It classifies the temperature conditions of the world and reveals

with great force the fact that the types of one continent are repeated in the others where the geographic factors determining temperature are similar.

6. It assists in clarifying the haziness that exists in the minds of many students regarding the temperature conditions of the tropics and the temperate and polar regions, for it shows the subdivisions of these regions in detail, yet not in such detail that the memory is burdened.

7. The map is simple and easily understood when once the basic principles are established.

William Gardner Reed.

Cotton.—Read by Title.

Cotton is grown commercially in only four or five countries, at least in such quantities that it has any appreciable effect on the world situation; cotton manufacturing is an important industry, in some eight or ten countries, and practically all the world is the consuming area for cotton goods. The result is that cotton has become a very important factor in commercial geography. Raw cotton has an important part of the export trade of the United States, Egypt, India and Peru. Cotton manufacturing is a leading industry of the United States, the United Kingdom and other European countries, and Japan. For none of these countries, except part of the United States can the supplies of cotton be obtained locally and for nearly all the raw material must be brought by sea for long distances. The regions where cotton may be grown are limited, the controls of the commercial crop being climatic and labor conditions. Cotton manufacturing apparently depends on a favorable factory development. International shipments of cotton and cotton goods, give rise to international bills of exchange in larger quantity than any other commodity, with the possible exception of grain.

G. T. Rude.

The Uses of Mean Sea Level in Determining Stability of Coast Lines.

The paper included a summary of the following topics:

The methods employed by the Coast and Geodetic Survey in determining mean sea level by a long series of tidal observations at the principal stations along the Atlantic Coast.

The distribution of the principal tidal stations along the Atlantic Coast.

The preservation of mean sea level by spirit level connections between automatic tides gauges and standard bench marks along the Coast.

Proposed plans for precise level connections between coastal bench marks and bench marks established in relatively older geological formations inland.

Carl O. Sauer.
Objectives of a Geographic Study.

M. W. Sentsius.—(Introduced by H. H. Barrows.)
Recent Views on Soil Classification.

Soil like climate is admittedly part of the human environment. But unlike Climatology the study of soils, for which the name pedology is coming into use, has not found adequate recognition in the training of geographers.

One of the first problems the pedologist has to solve to the satisfaction of the geographer is the development of an adequate soil classification. The prevailing classifications, primarily geological and physiographical in nature, for those very reasons cannot satisfy him. Recently noteworthy contributions have been made, especially by Russian and German workers toward a soil classification based largely on climate.

The newer views and principles were summarized.

H. L. Shantz.
The Natural Vegetation of the Great Plains.—Printed in full, ANNALS, June, 1923.

J. Russell Smith.
The Regional Map of North America.

The understanding of the relationship of the people to the land involves the divisions of the land into some kind of units. It also involves the consideration of the influence of many elements such as soil, surface, temperature, rainfall, humidity, location, minerals, and of many derivatives of the above such as plants, animals, industries, trade, people and their characterstics and government.

The question then arises, which shall we use as the basis of the division of our regions? The answer seems plain—no *one* in all cases, but the one or ones that really give character to a particular area. It may be surface, or climate, or location, or some other or others.

The map shown has some regions that are characterized by a crop such as spring wheat, which is in turn chiefly a climatic response. Another region is the Southern Rocky Mountains. Here the chief

characterization is surface and its resulting climates. Yet another region, the Erie Canal Belt, which includes the Hudson Valley, receives its chief characteristics as the home of man from the fact that it has unusual commercial access, a result of location, making it a great trading and manufacturing region.

Helen M. Strong.—(Introduced by J. Paul Goode.)
The Geography of Cleveland.

Cleveland is a city of contacts, a focus of natural highways. The only broad, fairly level, lowland route directly connecting the coal fields of Pennsylvania, Ohio, and West Virginia, with Lake Erie reaches the lake at this point. The mouth of the Cuyahoga is the intersecting point of three important routes, that extending east and west along the lake plain, the lowland pathway to the coal fields, and the deep water course through the Great Lakes. The valley-way is the major factor in locating, at the mouth of the Cuyahoga, the largest industrial center on the southern shore of Lake Erie.

The Cuyahoga valley is the notable topographic feature of Cleveland. It is the strategic contact for lake and land traffic, and so is crowded with steel mills, lumber yards, petroleum refineries, chemical plants, and associated industries. The industrial harbor is in the sharply meandering river, the commercial harbor is on the lake front.

Cleveland is an industrial city with important commercial activities. Three factors appear to have been chief in the development of Cleveland as a manufacturing city. (1) Cleveland is the lake terminus of the best lowland route from the Pittsburgh fields; (2) Mesabi Ore can be brought by way of the lakes at low freight cost; (3) Cleveland is located in the Northern Interior which provides a large and prosperous market for a wide variety of manufactured products.

This variety is a direct response to four influences. (1) Steel can be produced here more cheaply than elsewhere on the lakes; (2) Lake and land traffic bring a variety of raw materials to Cleveland, such as copper, wool, grain, oil and lumber; (3) Secondary industries have developed which use by-products of the primary industries; (4) The multiple demands of the prosperous markets in the Northern Interior also conduce to variety of products.

The commerce of Cleveland moves by rail and lake. Iron ore is the downbound cargo on the lake steamers, and coal the upbound cargo. Manufactured goods and merchandise chiefly are received and shipped by rail. Most of the traffic is with the East and West.

Stephen S. Visher.

Some Effects of the Tropical Cyclones of the Pacific.

A presentation of the areal and seasonal distribution of tropical cyclones in the Pacific was followed by a brief discussion of some of their obvious effects, together with inference as to their possible influence upon the distribution of life in the Pacific, upon the local diversity of climates, upon the multiplicity of tropical species, and upon certain other characteristics of animals, plants and man. The subject as to whether tropical disturbances may profoundly influence the weather of mid-latitudes by altering storm tracks and intensity, was also raised with the purpose of obtaining discussion.

O. D. Von Engeln.

The Regional Geography of Barbados, B. W. I.

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